Proceedings of the Nova Scotian Institute of Science (2023)
Volume 53, Part 1, pp. 83-122

POPULATION CHARACTERISTICS AND MOVEMENTS OF STRIPED BASS *MORONE SAXATILIS* (WALBAUM, 1792) IN THE MIRA RIVER ESTUARY, CAPE BRETON ISLAND, NOVA SCOTIA, CANADA

COLIN F. BUHARIWALLA[1], MICHAEL J. DADSWELL[1]*, SAMUEL N. ANDREWS[1], MICHAEL J.W. STOKESBURY[1] AND JOHN L. MACMILLAN[2]

[1]*Department of Biology, Acadia University*
33 Westwood Ave., Wolfville, NS B4P 2R6

[2]*Inland Fisheries Division, Nova Scotia Department of Fisheries and Aquaculture*
PO Box 700, Pictou, NS B0K 1H0

ABSTRACT

The occurrence of striped bass outside the immediate vicinity of known spawning rivers in Canada is neither widely understood nor well studied. Striped bass in Canada are managed and assessed within three distinct units, the Bay of Fundy, the Gulf of St. Lawrence, and the St. Lawrence River; but stocks that may occur outside these units are unrecognized. We document a previously unstudied aggregation of striped bass in the Mira River estuary (MRe), Cape Breton Island (46° 01′N, 60° 03′W), a location on the east coast of Nova Scotia omitted from present management units but which has been long reported to host an aggregation. From July 2012 to November 2014, 62 striped bass within MRe were sampled and 31 were surgically implanted with VEMCO acoustic transmitters. Striped bass ranged in size from 31.6 to 125.0 cm total length and age 3 to 24 years. Acoustic telemetry from 2012 to 2015 elucidated residency and fidelity to the MRe with mid-estuary overwintering every year, freshwater residency of the adult population during spring, and a summer through autumn aggregation in the lower estuary. Of the 31 acoustically tagged striped bass, 24 remained in MRe throughout the study, six exhibited mid-summer departures to the Atlantic Ocean but returned by mid-autumn, while one left the MRe and was never detected again. Mira River SB with acoustic tags were never detected at nearby Ocean Tracking Network telemetry infrastructure. Striped bass stocks exhibit similar residency and fidelity patterns to their natal rivers and estuaries elsewhere in its Atlantic coast range which

* Author to whom correspondence should be addressed: mike.dadswell@acadiau.ca

suggests the Mira River aggregation constitutes a possible distinct stock yet unrecognized by Canadian fisheries managers.
Keywords: acoustic telemetry, fidelity, wintering habitat, residency, zoogeography

INTRODUCTION

Anadromous fishes exhibit complex migratory strategies ranging from multi-year marine migrations to lacustrine residency (Borman & Lewis 1987, Hansen & Jonsson 1991, Dadswell *et al.* 2010), with intra-specific variation in timing and routes, and distinct intrapopulation contingents using multiple migration strategies (Clark 1968, Dadswell *et al.* 1987, Chapman *et al*. 2012, Gahagan *et al.* 2015). Contingents are differentially susceptible to anthropogenic perturbation, such as development, pollution, and exploitation, depending on the nature and scale of their migrations and are therefore important to identify (Buhariwalla *et al.* 2016, Keyser *et al.* 2016, Dadswell *et al.* 2018). Advances in acoustic telemetry and proliferation of telemetry research networks (O'Dor & Stokesbury 2009, Cooke *et al.* 2011, Hussey *et al.* 2015, Bangley *et al.* 2020) enables spatiotemporal resolution of movements ranging from fine scale foraging behaviour (McLean *et al.* 2014) to identification of previously unknown migratory patterns and contingents of fishes (Secor 1999, Keyser *et al.* 2016), and also provides data on critical habitat of importance for species of conservation interest (Dadswell & Rulifson 1994, Kessel *et al.* 2016, Crossin *et al*. 2016, Andrews *et al.* 2018).

Stiped bass *Morone saxatilis* (Walbaum, 1792) is a long-lived, economically, and ecologically important anadromous species native to watersheds and coastal regions of eastern North America from the Gulf of Mexico to Labrador (Merriman 1941, Scott & Scott 1988, Rulifson & Dadswell 1994, Robitaille *et al*. 2011, Andrews *et al.* 2019a). Throughout its range, striped bass support high value commercial and sport fisheries and has been subjected to various conservation measures including total allowable catches (TAC), commercial closures and risk assessment (Field 1997, Richards & Rago 1999, COSEWIC 2012, Broome 2014, ASMFC 2016). In Canada, however, commercial fisheries were closed by 1996 and the species is now managed to support recreational angling and First Nations' fisheries (Douglas *et al.* 2003, Bradford *et al*. 2012). Successful management of this euryhaline species depends on identification of the migratory strategies within the stock of interest (Able *et al.* 2012, Andrews *et al.* 2017).

Striped bass migratory strategies are highly variable. Stocks at the southern extreme of their range exhibit riverine and estuarine residency, potentially avoiding marine thermal barriers to coastal migration and survival (Hess *et al.* 1999, Bjorgo *et al.* 2000, Nelson *et al.* 2010). Stocks between North Carolina and New Brunswick exhibit long distant marine migrations (Setzler-Hamilton *et al.* 1980, Waldman *et al.* 1990, Rulifson *et al.* 2008, Mather *et al.* 2010, Douglas & Chaput 2011, Andrews *et al.* 2019a), however, otolith microchemistry analyses indicate the presence of riverine and estuarine resident contingents within some stocks (Secor & Piccoli 1996). These strategies are somewhat variable with marine migration demonstrated to increase with age. Further complicating the contingent concept, migratory striped bass take up residence in non-natal estuaries to which they often exhibit annual fidelity (Grothues *et al.* 2009, Mather *et al.* 2009, Pautzke *et al.* 2010, Gahagan *et al.* 2015, Andrews *et al.* 2018). These behaviors are well documented in American and Canadian stocks, however, in Canada information is limited and based on conventional tagging, fisheries observations, and telemetry projects focused near known spawning rivers (Douglas *et al.* 2009, Broome 2014, Keyser *et al.* 2016, Dunston *et al.* 2018, Andrews *et al.* 2019b).

Striped bass are known to occur along the eastern coast of Nova Scotia, north to Cape Breton Island coastal waters (Fig 1; Bigelow & Schroeder 1953, Scott & Scott 1988), and its inland sea, Bras d'Or Lake (Cash *et al.* 1985). Cape Breton straddles two management zones (Designatable Units - DUs) in which striped bass were assessed as threatened and/or endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012) but are unlisted in this region by the Canadian Species at Risk Act (SARA). Little published data exist on striped bass biology, populations, or movements within Cape Breton (Leblanc *et al.* 2020). There have been, however, significant angling catches in the region that have produced all-time Canadian angling records and Nova Scotia yearly angling records including 26.8 and 24.5 kg striped bass from Bras d'Or Lake and the Mira River estuary (MRe), respectively (NSDFA 2007, NSDFA 2018, Andrews *et al.* 2019a).

In this study we focused on the Mira River estuary in eastern Cape Breton (Fig 2). Striped bass were captured by angling for demographic assessment and acoustically tagged to evaluate their residency, movements, and potential migratory strategies. The objectives of this study were to: 1) examine population characteristics; 2) identify residency patterns and seasonal movements within the estuary; 3) identify critical estuarine habitat; and 4) detail interactions with the Ocean Tracking Network (OTN) telemetry infrastructure in the region (Fig 1). The biology of striped bass in the MRe was unknown before this study and conventional thought suggested these fish were a migratory contingent occupying the estuary for summer foraging (Leblanc *et al.* 2020).

We suggest that if the aggregation was a migratory contingent then striped bass would exhibit autumn migrations to wintering habitat near their natal systems OR exhibit spring migrations to spawn in natal systems. If striped bass exhibited annual residency within MRe,

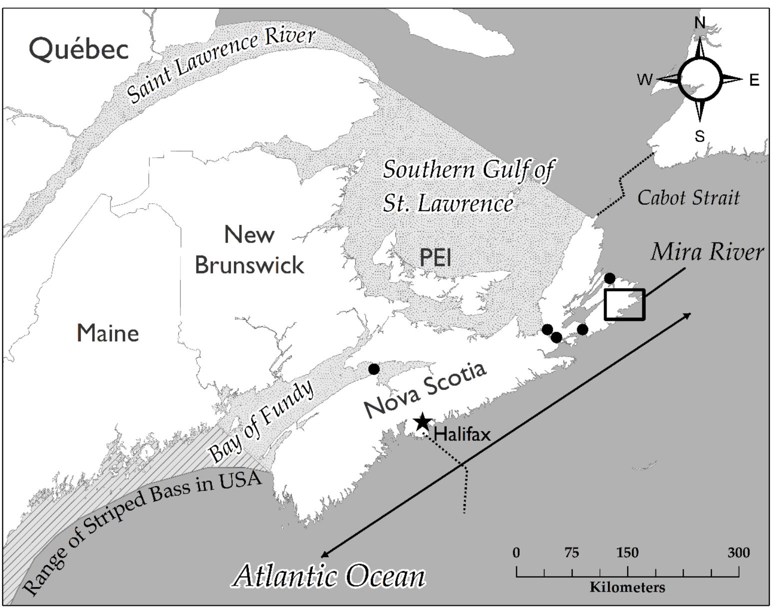

Fig 1 The location of the Mira River estuary and Ocean Tracking Network acoustic telemetry infrastructures deployed in Atlantic Canada during 2012-2015. Dotted lines indicate large-scale marine, telemetry arrays. Larger black dots indicate the location of smaller arrays that were deployed during the study period. The double pointed arrow along the Nova Scotia coast indicates the break in known Canadian striped bass stocks. Shaded regions are the Department of Fisheries and Oceans and COSEWIC designated zones for striped bass management. Crosshatching indicates the range of striped bass stocks in the United States.

especially during the spring spawning period, then these fish possibly constitute a previously undescribed spawning stock.

We postulate that striped bass adopt a life history strategy at the southern and northern ends of their Atlantic coast range that permits survival of stocks by utilizing freshwater refugia to avoid unfavorable marine environments. The results of this study may fundamentally change our understanding of the striped bass at the northern extreme of their range and should inform future research and management decisions.

STUDY SITE DESCRIPTION

The Mira River estuary located in eastern Cape Breton Island, Nova Scotia (Fig 1; 46° 01′N 60° 03′W) flows approximately 45 km from headwaters at MacMulins Lake to confluence with Mira Bay on the Atlantic coast (Fig 2). The drainage area of 645 km^2 encompasses many small brooks, with the only major tributary, Salmon River, located 11.5 km from the head of the system. The MRe was historically a chain of kettle lakes connected by small river channels (NSDOE 1976), however, recent submergence of the Atlantic Coast of Nova Scotia caused by post-glacial isostatic adjustment (1.2 m over the last 1000 years; Grant 1970, Bousfield & Thomas 1975) has resulted in flooding of the river valley to form large shallow bays (2-4 m deep) connected to the former lake sections (15-27 m deep) and tidal influence that extends to the head of the system.

Despite its name, the Mira River is essentially a large estuary. Surface waters throughout the estuary are dominated by freshwater discharge during periods of high precipitation in the spring and autumn, but during the summer a salt wedge penetrates the upper reaches of the estuary with salinity detected at the head of the system (0.1-0.2). Pycnoclines typically occurred all year in deep sections throughout the system at depths of ~3-6 m, while shallow sections maintain similar characteristics as the upper strata of nearby deep holes. Intermediate depths within the mid-estuary maintain greater temperatures in the late fall than surface or bottom waters. Anoxic conditions do occur in some of the deep holes when strong thermoclines and/or pycnoclines are present.

A HOBO U20-001-04 (Onset Computer Corporation, Cape Cod, Massachusetts) water level logger was used to measure tides in the mid estuary from July through November 2013. The logger was programmed to log water level (±0.3 cm) every 15 minutes and moored immediately upstream of Albert Bridge (Fig 2). HOBOware Pro was used to setup, download, and apply barometric pressure correction (obtained from Environment Canada's Sydney weather station) to observed water levels, while the 'R' package 'TideHarmonics' (Stephenson 2016) was used for analysis. A HOBO Pendant temperature logger was also deployed immediately upstream of Albert Bridge and recorded hourly temperature readings from July 2012 through May 2015.

Temperature, salinity (PSU), and dissolved oxygen (DO) were measured at stations throughout the MRE from May to November 2013 (Fig 2). Sampling was from a 5.5 m vessel and a GPS (Garmin Etrex HTC; accuracy ± 3 m) was used to navigate to stations. Bow and stern anchors were used to minimize boat drift and swing due to currents and wind. The water column was sampled using a YSI-63 for temperature/salinity and a YSI-550a for dissolved oxygen (YSI Inc., Yellow Springs, Ohio). Sampling was conducted at 0.5 m increments around pycnoclines, 1 m increments when gradients existed, and 2 m increments when the water column was homogenous for temperature and salinity–a change of less than 1.0°C or 1.0 PSU per meter depth.

Zones

Zones were chosen *a posteriori* based on movements and residency patterns of striped bass and to reflect natural divisions within the estuary. Zone 1 began at Mira Gut (Fig 2), the confluence of the MRe with Mira Bay and the Atlantic Ocean, and contained a channel 5-11 m deep, 70-100 m wide, and 3 km long that leads from the sea to a section of the lower estuary 1-5 m deep, 500-700 m wide, and 2.5 km long. Tidal currents in Zone 1 prevented sampling from the mouth of the system, however, sampling did occur at the head of the zone. Temperatures in Zone 1 during the open water season ranged from 9.1-23.3°C and 16.2-19.5°C at the surface and bottom, respectively, except for November when it increased from the surface to the bottom. Salinity during the open water season ranged from 8.2-19.9 and 24.2-28.0 at the surface and bottom, respectively, with increasing salinity through the summer and decreasing in autumn. Dissolved oxygen through the sampling period ranged from 6.3-9.7 mg/L.

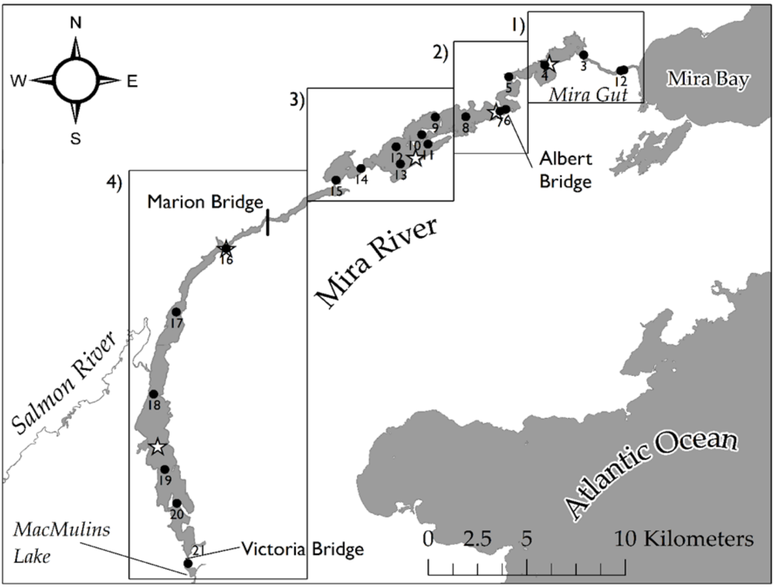

Fig 2 **The Mira River estuary flows 45 km northeast from its headwaters in MacMulins Lake to its confluence with the Atlantic Ocean at Mira Bay. The largest tributary, Salmon River empties into the Mira from the west, 11.5 km from the head of the system. The four study regions of the Mira River estuary delineated by boxes include 1) Mira Gut 2) Lower Estuary, 3) Middle Estuary, and 4) Lake. Acoustic receiver stations deployed along Mira River to detect tagged striped bass are indicated by numbered black dots (1-21) and temperature, salinity and oxygen monitoring stations within regions are marked by stars.**

Zone 2 was a 5 km long stretch of estuary ranging from 90 m to 1 km wide, and consisted of shallow coves, deep open bays, and a meandering channel 5-20 m deep. Albert Bridge crosses at the narrowest point of the zone and spans a channel 100 m long, 90 m wide with an average depth of 4-9 m. The channel straddles two holes, 16 and 20 m on the down and up estuary sides of the bridge, respectively, and was the main summer-autumn aggregation site for striped bass. The water level logger deployed on the inner estuary side of Albert Bridge observed mixed semidiurnal tides with mean tidal range of 19.1 cm.

Temperature during the open water season ranged from 9.1-24.1°C and 3.3-21.5°C at the surface and bottom, respectively (Fig 3). A thermocline occurred between 3-4 m depth in July, while during May and June temperature decreased more gradually with depth. Water temperature

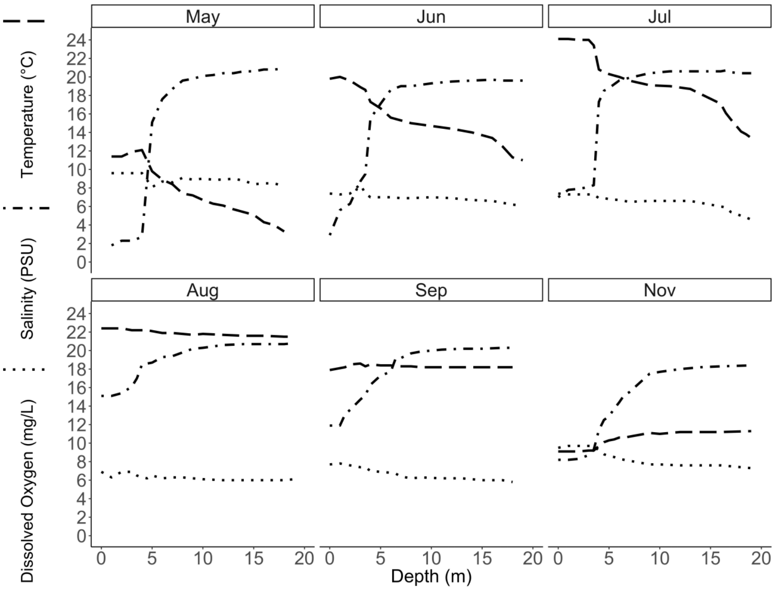

Fig 3 **Temperature (- - - -), salinity (- . - . – . -), and dissolved oxygen (…..) profiles in Zone 2 from May through November 2013, in the striped bass aggregation site at Albert Bridge on the Mira River estuary.**

was relatively homogeneous throughout the water column during August and September. The lack of thermal stratification is likely a result of tidal mixing given the sampling site was located immediately upstream of the narrows at Albert Bridge. Salinity during the open water season ranged from 2.9 to 15.1 on the surface and 18.4-20.9 on the bottom. A halocline was present at 3-4 m depth until August when salinity increased on a gradient versus a sharply defined halocline; the gradient was maintained until November. Dissolved oxygen ranged between 6.9-9.5 mg/L and 5.0-8.2 mg/L at the surface and bottom, respectively.

Zone 3 was approximately 7 km long with widths ranging from 70 m to 2.5 km (Fig 2). Channel depth ranged from 4-10 m with several shallow bays (2-4 m) on the north side of the estuary and a large (2 km long) deep (11-23 m) section on the south side of the lower portion of the zone identified as the critical striped bass wintering site.

Temperature during the open water season in Zone 3 ranged from 9.0-23.3°C and 4.8-8.1°C at the surface and bottom, respectively. Temperatures above and below the thermocline were homogenous through depth strata until August when surface temperatures cooled

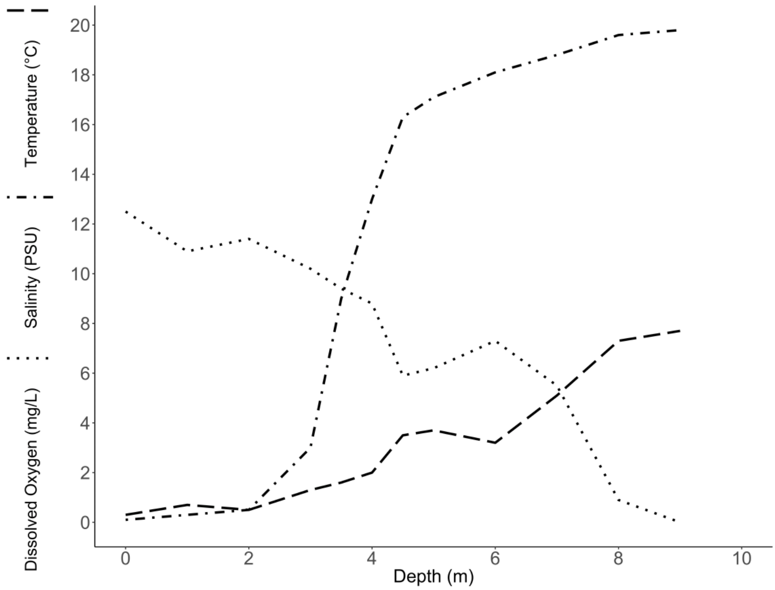

Fig 4 **Temperature (- - - -), salinity (- . - . - . -), and dissolved oxygen (……) profile from February 18, 2014, at the striped bass overwintering aggregation site in Zone 3 of the Mira River estuary.**

and the temperature difference between surface and bottom began to increase. Strata between 1-3 m cooled more rapidly in autumn than those deeper causing a warm-water layer between 4-8 m. Salinity during the open water season ranged from 1.7-13.9 at the surface and 19.4-20.4 at the bottom. The halocline occurred between 2.5-6 m and salinity variation was steepest in the spring becoming more gradual by autumn. Dissolved oxygen was 6.9-9.8 mg/L at surface and 0.0-3.8 mg/L at the bottom. Surface DO was relatively high throughout the sampling period; however, anoxic conditions were encountered on the bottom during July and DO was typically ≤ 4 mg/L below 10 m across all months.

Because of hazardous ice conditions during all years of the study only one profile of the striped bass wintering site was completed in February of 2014. Temperatures ranged from 0.3°C at the surface to 7.7°C near the bottom (9 m) with a distinct thermocline present at 6 m (Fig 4). Salinity ranged from 0.1 at the surface to 19.8 at the bottom with a halocline occurring between 3-4 m deep. Dissolved oxygen ranged from 12.5 mg/L at the surface to 0.0 mg/L at the bottom with a steep decline from 7 m to the bottom.

Zone 4 was 18 km long and ranged from 110 m to 1.8 km wide with a channel depth of from 3-27 m. The down estuary portion of the zone consisted of a meandering channel (3-8 m deep) that opened into a large lake section (6-27 m depth).

At the seaward end of Zone 4 during the open water season surface temperatures ranged from 9.5°C to 23.8°C while bottom temperature was 9.3°C to 23.3°C. This site was located above a constriction in the estuary and the water column was well mixed. No thermocline was observed from May through November. Salinity was 0.1 throughout the water column until salt wedge ingress in July and August when salinity ranged from 2.9-4.8 and 4.5-7.8 at the surface and bottom, respectively. Dissolved oxygen was relatively homogeneous throughout the water column during the monitoring period and ranged from 6.3 to 10.2 mg/L.

In the lake section of Zone 4 during the open water season, surface temperatures ranged from 10.3°C to 22.8°C while bottom temperatures ranged from 10.2°C to 18.7°C (Fig 5). A thermal gradient was present from June through August, however, from September onwards, water temperature was homogenous throughout

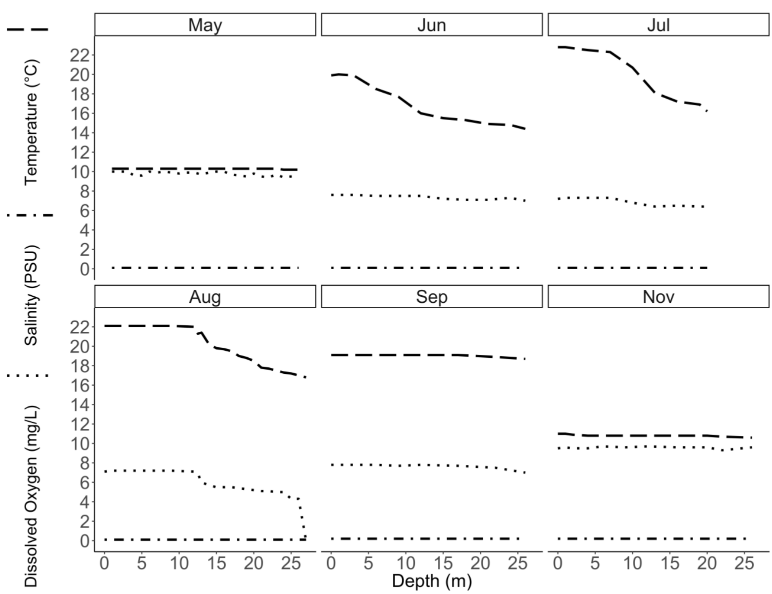

Fig 5 **Temperature (- - - -), salinity (- . - . - . -), and dissolved oxygen (…..) profiles from May through November 2013 in the Lake section of Zone 4 in the Mira River estuary.**

the water column. Salinity was 0.1 throughout the entire water column until September when it increased to 0.2 through to the end of sampling in November. Dissolved oxygen was typically homogeneous throughout the water column, ranging from 6.4 to 12.7 mg/L except during July when DO declined below 12.0 m and reached 0.0 mg/L near at the bottom (27 m), coinciding with the formation of the thermal gradient (Fig 5).

Fish Capture and Tagging

All striped bass except one were captured in Zone 2 at Albert Bridge (Fig 2) using rod and reel angling with 23 kg test braided line and 8/0-10/0 barbless circle hooks baited with available forage fishes or artificial fishing lures. Captured striped bass were immediately placed in an anaesthetic bath consisting of estuary water and 40 mg/L of a 10% Eugenol solution (clove oil, Hilltech, Vanleek Hill, ON: Lemm 1993). After 3-5 minutes, when opercular movements slowed, equilibrium was lost, and fish no longer responded to physical stimuli (running hand over the lateral line), they were sampled. Fork (FL) and total (TL) lengths were measured to the nearest 1 mm and weight (W) was obtained to the nearest 0.05 kg using a spring scale. Scales for aging were collected from above the lateral line between the two dorsal fins using forceps. A unique identifying dart tag (Floy® FT-1-94) with the address of Acadia University, Biology Department was inserted between the anterior pterygiophores under the first dorsal fin.

All striped bass considered large enough for acoustic tagging (body weight > 2% of tag weight) were then placed ventral side up in a padded V-shaped cradle on an incline, to ensure gills remained underwater, and intermittently irrigated with estuary water. Three rows of scales off the ventral midline were cleared from a patch ~2.5 cm long anterior to the anus. An incision ~2 cm long was made where a VEMCO® V13 transmitter (Bedford, Nova Scotia) was inserted into the body cavity, and the incision site closed with monofilament sutures (Ethicon® FS 5-0) tied with two horizontal mattress knots. All surgical tools were cold sterilized in 2% Gluteraldehyde (BM-28 PLUS; B. M. Group, Montreal, Quebec), while the transmitter and incision site (before and after surgery) were treated with 2% Chlorohexidine antiseptic (Stanhexidine Solution; Omega, Montreal, QC). Tools and transmitters were rinsed with sterile saline solution prior to use. Post-surgery, fish were recovered in gently flowing estuary water and released at the site of capture approximately 30 minutes after initial capture. All striped bass released with a transmitter were detected by receivers up and down estuary several days post tagging and all examined fish were considered to have survived handling and/or surgery. Tagging and surgery procedures were conducted under the Acadia University Animal Care protocol # 04-12 and a Department of Fisheries and Oceans Canada (DFO) scientific collecting permit # 337044.

Acoustic Telemetry

VEMCO® VR2w receivers were deployed and maintained from July 2012 to May 2015 at 21 stations in the Mira River estuary (Fig 2). Receivers were moored at 3-23 m depth in modified 17 x 40 cm PVC bullet floats with a 0.3-2 m nylon rope riser and anchored with ~20 kg nylon mesh bags filled with rocks. The initial array gated narrow (< 330 m) sections of the lower estuary to provide insight into behavior and inform future array design, since there was previously little knowledge of striped bass presence within the MRe. Due to limited number of receivers available to us, array configuration was modified across years to capture full extent of movements and to identify important habitat within the MRe. Sediment instability and transport in the lower section of the estuary and limited number of receivers resulted in no coverage within Mira Bay in the Atlantic Ocean outside of the estuary.

Range testing was carried out on all receivers. Because of the narrow nature of much of the estuary and lack of strong currents (except in Mira Gut) virtually every receiver could identify acoustic tags across the estuary except for those where the system was wider than 600 m (Fig 2).

The issue of false detections has been recognized to necessitate caution when dealing with acoustic detection datasets (Sipfendorfer *et al.* 2015). The White-Mihoff False Filtering Tool (White *et al.* 2014) was run in two stages. Stage one isolated individual tag numbers based on a subsequent detection interval of one second (s) to the minimum tag delay (50 s.); these detections could be created by detections on adjacent receivers or the collision of multiple tag transmissions. Stage two filtering used a detection interval of 60 minutes (*i.e.* solitary detections with ≥ 60-minute interval for preceding or following detection); these detections were then manually inspected and accepted or rejected based on behaviour of the 50 detections on either side of the suspect detection. If a single detection occurred at a station, the stations of previous and proceeding detections were compared to see if they occurred in a logical order (given the relative linearity of the system) and time. Detections identified as suspect were removed from the dataset.

Sample Description and Data Analysis

The geometric mean functional weight-length regression (equation 1; GMR, Ricker 1975) was performed using the log-transformed total length (TL mm) and weight (W kg) to calculate slope (*b*) and intercept (*a*) of the regression line where:

$$\log(\mathrm{W}) = \log(a) + b \cdot \log(\mathrm{TL}). \tag{1}$$

Due to unforeseen field events, only 57 of 62 sampled striped bass had associated weight measurements and were used in this analysis.

Striped bass scales were dried, cleaned in 70% ethanol, then mounted between two microscope slides for age analysis under a dissecting microscope (40X magnification, DeVries & Frie 1996). Three scales per fish were read by CFB and MJD. When disagreements occurred, we examined the specimen scales together and reached a consensus incorporating time of capture and length of the fish (Borgerson *et al.* 2014).

The Von Bertalanffy relationship was calculated using a plot of TL for age $t+1$ against age t to calculate TL∞ and K, and $\mathrm{Log}_e(\mathrm{TL}\infty - \mathrm{TL}_t)$ against age t to obtain to (Ricker 1975) where:

$$\mathrm{TL}_t = \mathrm{TL}\infty(1 - e^{-K(t - to)}). \tag{2}$$

The K is the Brody coefficient and to the hypothetical age at which the fish was zero TL.

Three of the 62 striped bass sampled had scales that were unreadable and were removed from the data set.

A Residency Index (I_R) was used to evaluate weekly residency within the four zones of the estuary over the period from April 25, 2013, to May 25, 2015. The residency index was calculated as the number of days a striped bass was detected out of the total number of possible days (Afonso *et al.* 2008) where:

$$I_R = \frac{\#\ of\ Days\ detected}{\#\ of\ possible\ detection\ days} \tag{2}$$

The total number of possible days incorporated time scale of interest (*i.e.* weekly), deployment history of the stations, and individual tag activity (based on tag battery life and period of interest). Due to a limited number of tags active during the spring, all years were pooled.

Departure events were defined as down estuary movement to the confluence with Mira Bay on the Atlantic Ocean, with an absence of detections within the array for 24 hours or greater and followed by subsequent detections ascending the estuary. The start and end of nautical twilight was used to delineate light and dark periods, respectively, and was obtained through the National Research Council Canada sunrise/sunset calculator (NRCC 2018). The Rayleigh Test for uniformity (Zar 2010, Pewsey *et al.* 2013) indicated whether departure and return events were uniformly distributed across multiple temporal scales and if a mean direction existed ($z_{0.05,\,13} = 2.937$) thus indicating directed movements were based on time of day.

The wintering period was defined as the first day an individual striped bass was exclusively detected within the wintering aggregation site (stations 11-13) to the first detection on a receiver in the outside array. Array design in 2012 did not allow for detection of striped bass within the wintering site so disappearance from the array during the up-estuary wintering migration was used as an approximate wintering start date. Since striped bass typically left the main aggregation site at Albert Bridge in late autumn to proceed to the wintering site, the last Albert Bridge (Station 7) detection was used to compare start of overwintering across years. The Watson-Williams test for homogeneity was used to determine if mean start and end of overwintering was different across years. The Kruskal-Wallis test was used to determine if there were differences in mean daily water temperature during the up-estuary wintering migration (November and December) and end of wintering (April and May) across years. When statistical differences occurred, the post hoc Dunn Test with Benjamini-Hochberg correction was used for multiple pairwise comparisons (Pohlert 2014).

All analyses were performed using R-statistical software (R Core Team 2013, Ogle 2014) and heavily relied on packages: ggplot2 (Wickham 2009), dplyr (Wickham & Francois 2015), tidyr (Wickham & Grolemund 2017), lubridate (Grolemund & Wickham 2011).

RESULTS

Sample Description

A total of 62 striped bass were sampled within the Mira River estuary from July 2012 to November 2014, of which 61 were captured at Albert Bridge while one was captured downstream of Station 17 (Fig 2). Sampled fish ranged in size from 31.6 to 125.0 cm TL and weight from 0.35-20.55 kg (Table 1). Striped bass ages ranged from 2 to 24 years.

The weight-length GMR was:

$$\text{Log W} = 2.929(\ (R2 = 0.9915)$$

where the slope (*b*) is 2.929 (2.55—3.31, 95% CI).

The Von Bertalanffy relationship calculated for the MRe population was:

$$TL_t = 128(1\text{-}e^{-0.12(t - 0.33)}) \text{ where } TL\infty = 128 \text{ cm and } K = 0.12.$$

Striped bass that were acoustically tagged were significantly larger than released non-acoustic tagged fish (Table 1; Welch's t-test; $P <$ 0.001).

The acoustic transmitter battery life varied across tag type (Model #, Table 1), thus the number of concurrently active tags within the system varied through time from a low of 5 to a high of 20. Monthly cumulative active transmitters (*i.e.,* number of transmitters active in each month), across years, ranged from a low of 11 in April-May to a high of 30 in November.

From July 2012 to May 2015 there were 1,297,708 acoustic detections registered to tags deployed within the MRe telemetry array. Using the White-Mihoff false filtering technique, 10,101 detections (0.78%) were considered suspect and discarded from analyses. Suspect detections predominantly occurred at aggregation sites within the system (Stations 6, 7, 11, and 13), and were likely the result of signal collisions or two receivers detecting the same transmission concurrently.

Residency

Residency within the MRe was seasonally concentrated in Zones 2 and 3, with limited residency in Zones 1 and 4 (Fig 6). Overwintering occurred at a winter aggregation site (stations 11, 12 and 13) within Zone 3 from late-autumn (mid-November/early December) through to

Table 1 **Tag information, morphometrics [total length (TL) and weight (W)], and group membership of striped bass acoustically tagged in the Mira River estuary from 2012-2014.**

Tag ID	Type	Tag life (days)	Date Applied	Activity (days)*	TL (cm)	W (kg)	Group
2012							
48407	V13-1L	793	Jun-19	888	61.4	-	B
48408	V13-1L	793	Jun-19	885	69.5	4.05	B
48409	V13-1L	793	Jun-20	889	73.4	4.35	B
48410	V13-1L	793	Jun-20	889	90.6	7.85	B
48411	V13-1L	793	Jun-20	889	72.4	3.85	B
48418	V13-1L	793	Jun-26	681	125	19.50	C
5720	V13P-1H	162	Jun-26	143	74.4	4.35	A
5721	V13P-1H	162	Jun-26	152	66.4	3.05	B
5722	V13P-1H	162	Jun-26	150	63.6	3.00	A
5723	V13P-1H	162	Jun-28	150	84.4	-	B
5724	V13P-1H	162	Jul-04	144	85.6	6.75	B
5725	V13P-1H	162	Jul-06	142	76.9	4.30	B
5726	V13P-1H	162	Jul-06	142	77.6	5.00	A
5728	V13P-1H	162	Oct-06	57	84.4	6.55	A
2013							
33158	V13-1L	881	Jun-26	698	69.3	3.35	B
33160	V13-1L	881	Jul-12	683	75.3	4.50	A
33159	V13-1L	881	Jul-12	683	63.2	2.45	A
33161	V13-1L	881	Jul-12	683	63.7	3.05	B
5729	V13P-1H	162	Jul-25	179	52.8	1.50	B
5730	V13P-1H	162	Jul-25	651	49.7	1.35	A
33162	V13-1L	881	Aug-13	180	90.0	7.45	A
5732	V13P-1H	162	Aug-13	180	79.9	6.20	A
5733	V13P-1H	162	Aug-22	180	50.0	1.35	A
5734	V13P-1H	162	Aug-27	180	66.3	2.85	A
5735	V13P-1H	162	Aug-27	32	69.1	3.60	**
5736	V13P-1H	162	Aug-29	180	82.5	5.45	B
5737	V13P-1H	162	Sep-22	180	51.0	1.50	A
5738	V13P-1H	162	Sep-22	180	49.9	1.30	B
5739	V13P-1H	162	Nov-11	179	57.3	2.30	***
2014							
5742	V13P-1H	162	Sep-13	179	61.0	2.00	****
5743	V13P-1H	162	Sep-13	170	53.8	1.60	****

* Deployment date until last day detected on the array.
** Left estuary 31 days after tagging and did not return.
*** Striped bass tagged too late to definitively resolve movements to the mouth of the system.
**** Telemetry coverage was not in place to resolve migratory group.

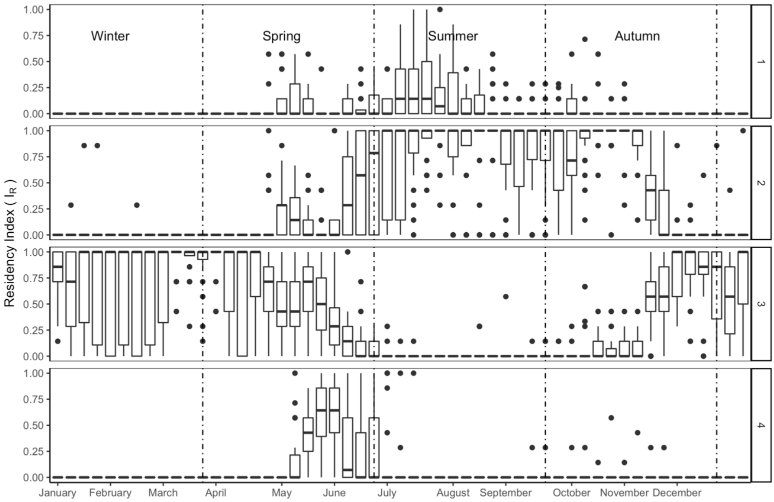

Fig 6 Weekly striped bass residency index (IR), pooled across years, in the Mira River estuary from Zones 1-4 during April 25, 2013, to May 25, 2015. Season delineations are based on equinox dates. Vertical bars represent range, boxes one standard deviation and black horizontal bars, mean residency index. Black dots represent receptions of single fish for short periods.

mid-spring (end of April/first two weeks of May) with median weekly IR ranging from 0.57 to 1.00. December through mid-May weekly median I_R within Zones 1, 2 and 4 was 0.00. Striped bass exhibited residency throughout all zones within the system in mid-spring (Fig 6), however, for two weeks at the end of May-start of June, median IR was greatest (0.64) in Zone 4. Residency shifted to an aggregation area located at the Albert Bridge capture site within Zone 2 at the end of spring. Summer residency was concentrated in Zone 2 at the aggregation site, however, median IR did increase 0.14 in Zone 1 relative to the rest of the year. High residency at Zone 2 persisted throughout the summer and autumn with median IR of 1.00 for all but one week between July and November before striped bass migrated to the up-estuary wintering site in Zone 3.

Seasonal use of the estuary was largely similar among telemetered striped bass, but detection histories suggested three different residency patterns (Fig 7). Group A (n = 12) utilised Zones 2 and 1 during the summer, however, this group made no attempt to leave the estuary–fish were not detected in the Mira Gut channel (stations 1-3) to the Atlantic Ocean. Group B (n = 14) exhibited similar residency patterns, however, this group moved down to the confluence of

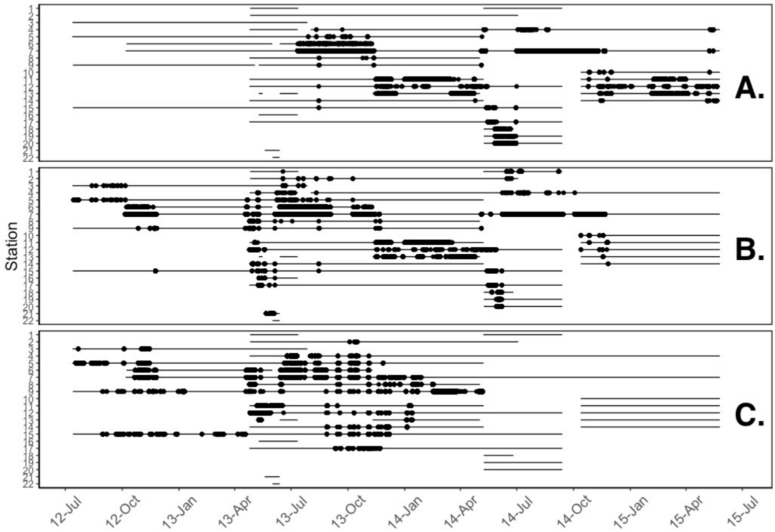

Fig 7 **System wide activity for three striped bass with multiyear tags within the Mira River estuary: A) ID 33159 exhibits typical residency patterns remaining within the system for the duration of the study. B) ID 48409 exhibits typical residency patterns, but also exhibits departure events. C) ID 48418 exhibits residency, however, it does not overwinter within the winter aggregation site (the only tagged fish to exhibit such behavior). Station deployment history is indicated by horizontal lines.**

the estuary with the ocean, and, in some instances left the system. Group A typically exhibited greater I_R throughout the system than group B (Fig 8), but most notably during spring and summer residency of Zones 4 and 1, respectively. Greater I_R values could, however, be a result of greater number of tags active within group B. Median residency in Zone 4 increased concurrently for both groups, but Group A peaked (I_R 1.00) one week earlier than Group B (I_R0.71) and maintained high levels of residency through the second week of July, while Group B departed Zone 4 by the second week in June. Residency index in Zone 1 peaked early in the summer for both groups, but median I_R for Group A reached 0.71 while Group B only exhibited an I_R of 0.14. Both groups, however, exhibited annual seasonal fidelity (high and relatively exclusive I_R) to summer and winter aggregation sites (Fig 8). There was no significant length difference between the two groups (*Welch's test*; $P = 0.758$, df: 24).

Group C consisted of one fish (ID 48418; Fig 7) that was 125.0 cm TL. This striped bass did not aggregate at the wintering site and was found throughout Zones 2 and 3 during the winter and spring but

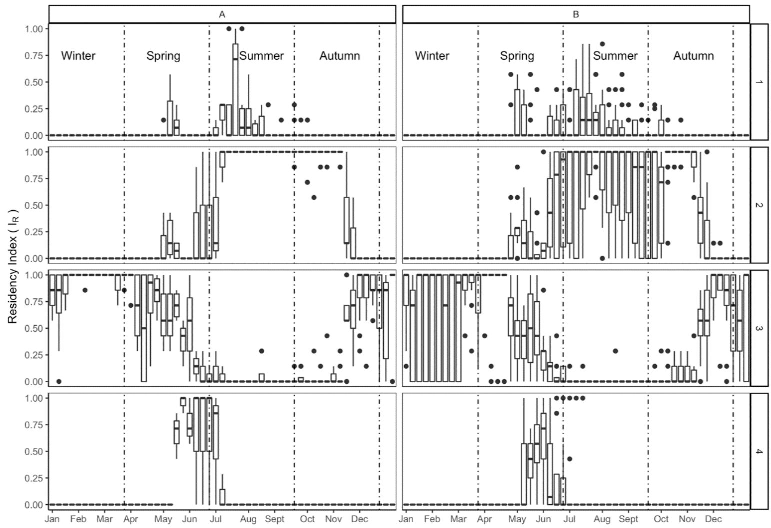

Fig 8 **Weekly striped bass residency index (IR), pooled across years, for migratory groups A (left) and B (right) from Zones 1-4 in the Mira River estuary during April 25, 2013, to May 25, 2015. Season delineations are based on equinox dates. Vertical bars are range, the box one standard deviation, and the horizontal bar, mean residency time.**

summer residency was concentrated within Zones 1 and 2, like groups A and B. Autumn residency, however, occurred throughout the entire system including Zone 4. While this striped bass was detected in the channel leading to the ocean, it did not exhibit departure events.

Departure Events

Due to logistical challenges, no receivers were deployed in Mira Bay, however, directed down estuary movements, a lack of detections within the array, observations of striped bass descending past a wharf at the mouth of the system (CFB, personal observation), and angler reports of capture events outside the river mouth (John Couture, local angler; Pat Young, DFO; personal communication) indicated the occurrence of departure events. One telemetered striped bass (ID 5735) left the estuary, 31.8 days post tagging, and was not subsequently detected within the MRe array. Despite proximity to OTN, Bras d'Or Lakes, Canso Strait, and Halifax receiver arrays, no telemetered striped bass from MRe were detected by the telemetry infrastructure in the region (Fig 1).

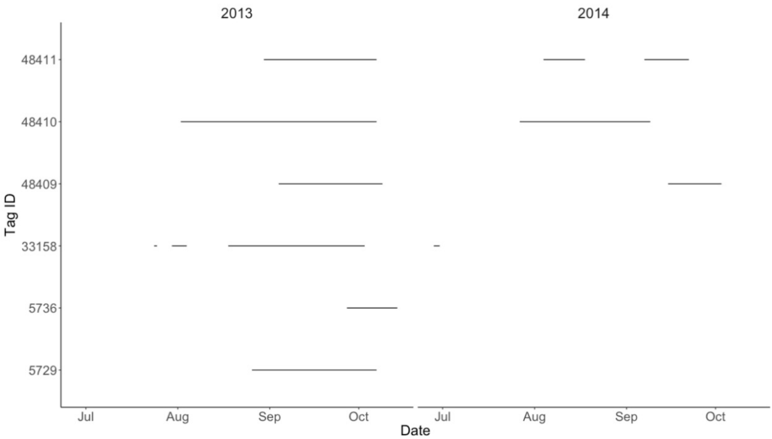

Fig 9 Gantt chart of striped bass departure events in the Mira River estuary (n = 13). Horizontal lines indicate time spent outside of the system by each acoustically tagged individual (tag ID).

Six fish exhibited 13 departure-return events during 2013 and 2014 (Fig 9). Four striped bass with multiyear tags displayed departure-return events across the two years, two of which exhibited multiple events within years. Departure and return events were not random for day of the year (Rayleigh Test for uniformity, $P < 0.001$) and occurred between June and October with mean exit and return dates of August 17th ± 25 days (mean ± SD) and September 14th ± 33 days, respectively. Striped bass left the MRe for 26.5 ± 20.1 days (mean ± SD), however, fish that exhibited multiple within-year departure events had highly variable absences (Fig 9). Striped bass exit-return events were not uniformly distributed by time of day (Rayleigh Test for uniformity, $P < 0.001$), primarily occurring at night. One departure event occurred in the morning (after the start of twilight, but before sunrise), while one return event occurred mid-day. All other departure and return events occurred at night (Fig 10). Mean exit and return times were 0225 UTC ± 1.8 hours (mean ± SD) and 0521 UTC ± 3.1 hours, respectively. Length of striped bass that exhibited departure events ($n = 6$) was not significantly different (Wilcoxon Rank Sum Test, $P = 0.4093$) than those that remained within the MRe (n = 24). The remainder of acoustically tagged fish remained within the estuary for the duration of their tag battery.

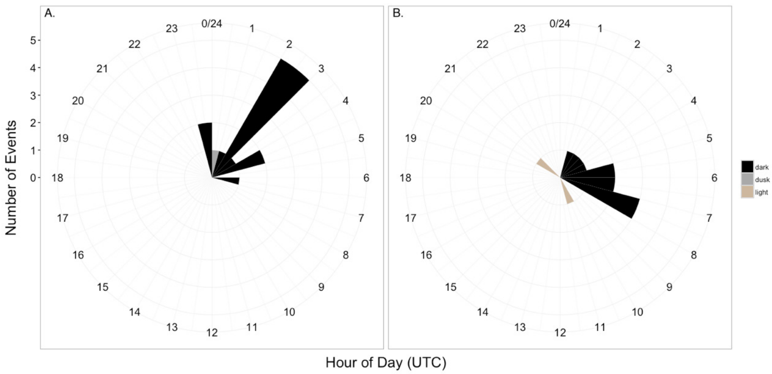

Fig 10 **Timing of striped bass departure (A) and return (B) events in the Mira River estuary. Colour of bars indicate light levels at time of departure/return event (black = dark, grey = dusk, tan = light). Length of bars indicate number of events to occur within the hour.**

Overwintering

Of the 31 telemetered striped bass, 30 overwintered within the MRe between 2012 and 2015 and 29 occupied the mid-estuary wintering site (Fig 2, Stations 11-13). Migrations for wintering occurred from Albert Bridge (Station 7) tagging site to the wintering site 5.5 km up estuary, starting mid-November and ending by the first week of December (Table 2). The up-estuary migration lasted 3.22 ± 5.21 and 1.26 ± 1.08 days (mean ± SD) for 2013 and 2014, respectively. The wintering period lasted until the end of April and into May with a duration of 160.19 ± 11.05 days (mean ± SD). Wintering duration was shortest for the winter of 2012-2013 with start and end dates later and earlier, respectively, than the following winters (Table 2). The mean date of departure from Albert Bridge for overwintering in 2012 was significantly different from the following winters 2013 and 2014, (Watson-William's test; $P < 0.05$), but no significant difference was observed between mean date of departure and arrival at the wintering site for 2013 and 2014 (Table 2). The mean wintering period end date was significantly different across all three years (Watson-Williams test; $P < 0.05$) and was later in each of the three successive springs (Table 2).

Daily mean water temperature during the November and December winter migration (Fig 11) was significantly different across years (Kruskal-Wallis χ^2 13.48, df = 2, $P = 0.0012$). *Post hoc* multiple pairwise comparison indicated that 2012 was significantly

TABLE 2 The timing of yearly striped bass migrations from Albert Bridge aggregation site to the wintering site and departure from the wintering site in Zone 3 of the Mira River estuary from 2012–2015. Units for standard deviations are days. Dates within the same column with different superscript letters were significantly different (Watson-Williams test; $P < 0.05$).

		Last Albert Bridge	Start of wintering		End of wintering			Duration
Winter	N	(mean ± SD)	mean ± SD	Range	N	mean ± SD	Range	mean ± SD
2012-2013	13	Nov. 24 ± 3.71[a]	Nov. 25 ± 3.32*	Nov. 16-Dec. 02	5	Apr. 20 ± 3.21[d]	Apr. 18-Apr. 26	146.28 ± 3.56
2013-2014	19	Nov. 15 ± 4.13[b]	Nov. 19 ± 5.40[c]	Nov. 12-Dec. 05	11	May 01 ± 6.10[e]	Apr. 24-May 12	163.46 ± 9.45
2014-2015	11	Nov. 19 ± 4.37[b]	Nov. 23 ± 6.07[c]	Nov. 10-Dec. 02	5	May 09 ± 2.65[f]	May 06-May 13	166.91 ± 6.84

* The wintering site acoustical array was not deployed for the winter of 2012-2013 thus the last detection on the Albert Bridge array was used as overwinter start date and the results could be compared to following years.

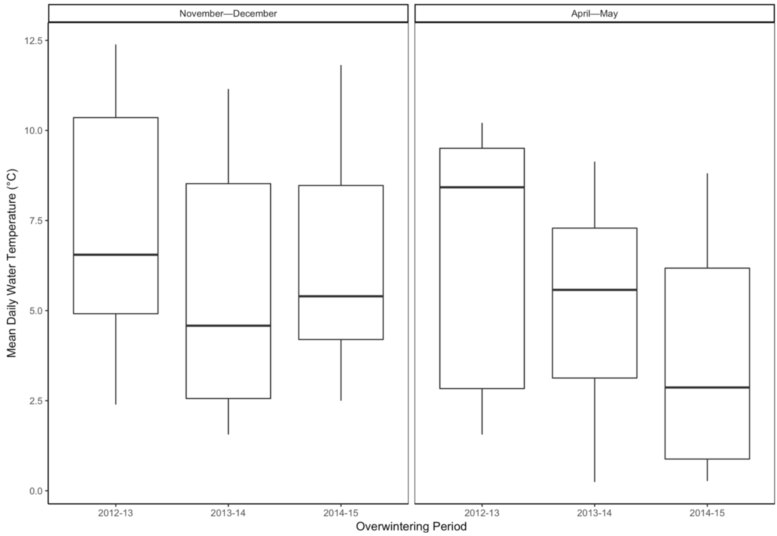

Fig 11 Boxplot of mean daily water temperature recorded at Albert Bridge during the months at the start (left) and end (right) of the striped bass overwintering period in the Mira River estuary across three years. Range is indicated by vertical lines, mean, by horizontal line. Letters indicate significant differences from multiple pairwise comparisons between temperatures within the panel (Dunn Test, $\alpha = 0.05$).

different (a, warmer) than 2013 and 2014 (Dunn Test; $P = 0.0008$ and $P = 0.0350$, respectively), however, 2013 was not different from 2014 (b, Dunn Test; $P = 0.1721$). Temperature differences also occurred across years at the end of the wintering period during April and May (Kruskal-Wallis χ^2 26.87, df = 2, $P < 0.0001$) and followed a similar pattern to the end of overwintering date (Table 2) with successive springs colder than the previous. Mean daily water temperature for April and May 2013 was significantly warmer than for 2014 and 2015 (c, Dunn Test; $P = 0.0282$ and $P < 0.0001$, respectively), while 2014 was warmer than 2015 (d, Dunn Test; $P = 0.0044$).

DISCUSSION

Population Characteristics

Size structure of striped bass sampled in the Mira River estuary exhibited differences relative to historical data from other Canadian stocks. Reported length frequencies for the Shubenacadie-Stewiacke and Miramichi rivers contained few larger individuals (>90 cm TL;

Robichaud-Leblanc *et al.* 1996, Douglas *et al.* 2009, Bradford *et al.* 2012), however, studies in the Annapolis and Saint John Rivers in the outer Bay of Fundy, indicate that large individuals were present (Rulifson & Dadswell 1995, Dadswell *et al.* 2018, Andrews *et al.* 2019b). More recent trap-net catch data from the Shubenacadie and Miramichi rivers (Douglas *et al.* 2003, DFO 2017) are consistent with historical data with length frequencies not exceeding 90 cm TL. A negative size bias may be associated with these trap net data as anglers report large striped bass (females to 121 cm TL and males to 97 cm TL) were frequently caught on the spawning grounds in these rivers (Owen Marr, local angler; personal communication; S.N. Andrews, personal communication). Similarly, the absence of size classes < 30 cm TL in the MRe is probably a result of our gear, bait size, and angling site selectivity.

All but one of the sampled striped bass were captured at the Albert Bridge sampling site but only one small fish (33.2 cm TL) was captured there. The striped bass not captured at Albert Bridge was 31.6 cm TL and was caught 14 km up-estuary. This is consistent with reports of 20 to 30 cm striped bass caught during the early 2000's in a small tributary 10 km up-estuary from Albert Bridge (Cruise Slater, local resident; personal communication). It is not surprising that there is a lack of captures of small fish given typical ontogenetic shifts in estuarine habitat reported for striped bass (Robichaud- LeBlanc *et al.* 1998, Able & Grothues 2007). Our sampling, however, was prioritized for the deployment of acoustic tags.

Residency within the Mira Estuary

Residency and fidelity to summer and winter aggregation sites was evident across years throughout the study period. This behaviour was typical for striped bass containing acoustic tags with both half-year and multiyear battery life. Evidence for residency and fidelity beyond the telemetry study was obtained through tag returns from recreational anglers. Acoustic transmitters were returned up to three years post release. In one instance a recaptured fish (ID: 33161) was caught October 22, 2015 at Albert Bridge, two years to the week after initial tagging; then harvested from the same site one year later, on October 25, 2016 (C. Paul, Unama'ki Institute of Natural Resources; Joe Sylvester, local angler; personal communication). Acoustic telemetry of striped bass in the MRe revealed interannual residency, site fidelity, seasonal movements, and contingent behaviour consistent with populations elsewhere in the range (Rulifson & Dadswell 1995, Wingate *et al.* 2011, Gahagan *et al.* 2015, Andrews *et al.* 2018), and, with the presence of a critical overwintering site, potential spawning, and foraging habitat, suggests the MRe population may constitute a discrete stock.

All telemetered striped bass that exhibited residency in the MRe remained within the mid-estuary throughout the winter and, of these residents, all but one utilized the mid-estuary wintering site across years. The up-estuary migration for wintering was spatially and temporally limited compared to other striped bass populations consisting of only a 5.5 km up estuary movement over 1-3 days between mid-November and the first week in December. Winter residency in the Mira, however, was among the longest known throughout the striped bass range persisting into the first week of May (Andrews *et al.* 2019c). Kneebone and co-workers (2014) observed mixed stock wintering migrations of 300 to 700 km southward from Massachusetts in November with striped bass arriving at coastal and estuarine overwinter sites in the Chesapeake Bay and Hudson Rivers by December. These telemetered fish are detected moving into spawning rivers by late February and early March. A freshwater overwintering contingent (Paramore & Rulifson 2001) within the Bay of Fundy's Shubenacadie population migrates a minimum of 50 km into Grand Lake from October through November (Bradford *et al.* 2012) where they remain until May (Douglas *et al.* 2003). A marine overwintering contingent, however, remains within the Minas Passage of the inner Bay of Fundy from December through March (Keyser *et al.* 2016). In the Saint John River, NB, the OWS occurs primarily in Belleisle Bay, an estuarine lake, and lasts from mid-October until April (Andrews *et al.* 2020). In the Kouchibouguac River, 50 km south of the Miramichi R., striped bass overwinter from December through the start of April (Bradford *et al.* 1998). Miramichi River striped bass migrate back to their natal estuary from around the sGSL to overwinter from late fall to early May; non-natal estuaries across the sGSL are opportunistically used as wintering sites (Rulifson & Dadswell 1995, Bradford *et al.* 1998, Douglas *et al.* 2003, Buhariwalla *et al.* 2016) with returns to the Miramichi (often > 350 km) occurring in May (Douglas *et al.* 2009, S. Douglas, DFO, personal communication, CFB, unpublished data). The historical St. Lawrence River population had migrated to freshwater wintering sites near spawning sites, approximately 400 km upriver, beginning in late September to early October where they remained until spring spawning in mid-May (Magnin & Beaulieu 1967, Robitaille *et al.* 2011). The observed latitudinal variation in overwintering timing and duration across the range is thought to be a function of water temperature and salinity as osmoregulation at lower temperatures and high salinities is metabolically expensive resulting in the requirement for winter refugia (Hurst & Conover 2002).

Previous studies indicate the use of a wide variety of overwintering habitat among and within stocks. Gahagan and co-workers (2015) demonstrated that striped bass overwintered in the lower Hudson River estuary and nearby coastal waters. Shubenacadie-Stewiacke River striped bass (Bay of Fundy) utilize freshwater (Rulifson & Dadswell 1995, Bradford 2012) and marine (Paramore & Rulifson 2001, Keyser *et al.* 2016) winter habitat, while estuarine and freshwater overwintering is common throughout the southern Gulf of St. Lawrence (Rulifson & Dadswell 1995, Bradford *et al.* 1998). Striped bass also overwinter in warmwater discharges from power generating plants throughout its range (Williams & Walden 2010, Buhariwalla *et al.* 2016). The MRe wintering site was likely used since it was a deep embayment with relatively stable temperatures (~5-10°C) through much of the winter (Coutant 1985), and since it was protected from cool waters of the shallow section of estuary above, and from the cold tidal waters down estuary. Given the west-east orientation of the wintering site, and many small islands to the north and to the shore to the south, the site remained relatively protected from autumn south-westerly and winter northerly winds (especially after ice formation). A lack of turnover allowed water column stratification to persist as surface water air cooled and surface salinity was dominated by runoff and river flow resulting in the mid to lower strata retaining trapped heat while dominated by intermediate salinities. At the end of the winter, however, the wintering site did turn over.

Spring Residency

After the overwintering period, residency from mid-May to early July was highest in the upstream (Zone 4) freshwater portion of MRe. Outside of land-locked reservoir populations, spring freshwater use is typically associated with spawning activity (Setzler-Hamilton & Hall 1991, Wingate *et al.* 2011), with residency in the MRe coinciding with the spawning period reported for northern populations (Setzler *et al.* 1980, Dunston *et al.* 2018, Andrews *et al.* 2019b). Spawning in the Shubenacadie-Stewiacke system occurs from late May through mid-June (Rulifson & Tull, 1998, McInnis 2012). In the Miramichi River, the closest recognized stock to the MRe, spawning occurs for 3-4 weeks in late May through late June (Robichaud-LeBlanc *et al.* 1996, Douglas *et al.* 2009). No spawning behavior was observed, and no eggs or larvae were collected in the MRe (CFB, unpublished data), however, we observed one running ripe male and three spent females that were captured by anglers and anglers reported milting striped bass in the freshwater zone after our fieldwork was completed (K. Hutchins and A. Hunt, personal communication). It is not possible to say for certain if spawning occurs within the MRe, but patterns of residency match those of spawning populations whereby overwintering is followed by migrations to and residency in freshwater with subsequent migrations to summer foraging sites.

Summer/Autumn Residency

Residency of MRe fish shifted to Albert Bridge (Station 7) and to a minor extent, the lower estuary from summer through late autumn. Annual fidelity of striped bass to summer feeding sites is widely documented (Ng *et al.* 2007, Wingate & Secor 2007, Mather *et at.* 2009, Kneebone *et al.* 2014) and estuarine distribution is often associated with shoreline or bathymetric structure and strong currents. Striped bass tend to concentrate around artificial structures such as bridge pilings and associated shoreline anchor stone (Haeseker *et al.* 1996), natural structure of submerged woody debris (Wilkerson & Fisher 1997), mussel and oyster beds (Harding & Mann 2003), and/or bathymetric relief (Ng *et al.* 2007). The MRe summer aggregation site occurred where the system narrows from ~ 1000 m across and 14-19 m depth (both up and downstream) to a 100 m long stretch that is 80 m wide and 3-10 m deep. Bridge pilings, associated anchor stone, natural rock bars, and oyster beds resulted in diverse physical structure and combined with tidal currents, concentrated striped bass. Summer residency also occurred, to a lesser extent, in the lower MRe as half of tagged fish moved down estuary to the confluence with the Mira Bay/Atlantic Ocean. A small subset of these fish left the system for up to two months, however, they returned to the Albert Bridge aggregation site until the fall migration to the wintering site. Different summer residency strategies among telemetered striped bass indicate that complex migratory behaviours, typical of populations elsewhere, also occur within the MRe.

Contingent Behaviour

Striped bass contingent behaviour is an excellent example of partial migrations (Chapman *et al.* 2012, Gahagan *et al.* 2015), whereby multiple migratory strategies exist within or between populations. For example, the Chesapeake Bay and Hudson River stocks are comprised of three contingents: freshwater, estuarine, and coastal migratory contingents as defined by habitat used by post-spawning adults (Secor & Piccoli 2007, Wingate & Secor 2007, Wingate *et al.* 2011). Coastal migratory contingents are further complicated by sub-groups that exhibit residency and often express annual site fidelity in non-natal estuaries (Mather *et al.* 2009, Grothues *et al.* 2009, Patzuke *et al.* 2010, Kneebone *et al.* 2014, Andrews *et al.* 2018). Able & Grothues (2007) found that some coastal migrants occupied the Mullica River-Great Bay, New Jersey and Saco River, Maine estuaries from spring through late autumn. In a concurrent mobile telemetry study non-natal migrants were identified that exhibited annual residency and site fidelity on a scale of several meters within the Mullica River-Great Bay system (Ng *et al.* 2007). These non-natal residents typically return to natal systems (or nearshore coastal environment) in autumn to prepare for the spring spawning run (Mather *et al.* 2010, Kneebone *et al.* 2014, Gahagan *et al.* 2015). Some individuals, however, remain in non-natal systems year-round only returning to spawning sites in the spring, then promptly returning to the non-natal system (Andrews *et al.* 2018).

The contingent behaviour and partial migrations which occurred within the MRe appeared like those found within other stocks. Three distinct groups were observed in the MRe: groups A (n = 12) and B (n = 14) followed the cycle of overwintering at the main aggregation site, spring freshwater residency, autumn residency at the lower-estuary aggregation site, and then migration back to the wintering site. Group A remained within the estuary and made no excursions to the mouth of the system. Group B ventured to the mouth of the system with some individuals (n = 6) exiting the system for up to two months. Group C (n = 1) remained within the mid- to lower-estuary but did not occupy the main winter aggregation site and did not leave the system. These groups may represent A) estuarine residents, B) a mixture between estuarine residency and local marine residency, and C) undefined since only one individual exhibited this behaviour. Given that these fish remained within the system during winter, exhibited spring and summer freshwater residency (groups A and B), and those that made marine departures returned by mid-autumn, it appears that the MRe striped bass are local in origin and may constitute a spawning stock even though genomic analysis of MRe fish suggested they have a mixture of US and Miramichi genotypes (Leblanc *et al.* 2020).

Contingent behaviour in other coastal ecosystems perhaps suggest migratory groups exist within the MRe (*e.g.* freshwater residents, coastal migrants). These groups, if present, were unlikely to be intercepted and sampled in our study given the timing and location of our sampling was June through November at one site in the lower estuary. A potential freshwater contingent would remain in the headwaters of the system until down-estuary migration to wintering sites (Wingate & Secor 2007), while a migratory contingent would move to the ocean immediately after freshwater spawning (Douglas *et al.* 2009, Gahagan *et al.* 2015). The best chance to sample these potential contingents would either be on the wintering grounds or during upstream spring spawning migrations, however, with exception of using dorsal colouration as an identifier of marine overwintering (Paramore & Rulifson 2001), differentiation between contingents would have been nearly impossible at the time of our sampling. A migratory contingent was not encountered during the spring alewife (*Alosa pseudoharengus* Wilson, 1811) fishery in the lower estuary (J. Horne, K. Nichols, commercial alewife fishers; personal communication), however, there are several explanations for this: 1) gill mesh size used in the MRe is not selective for spawning size striped bass (Trent & Hassler 1968); 2) the commercial alewife season ends by early June and does not overlap with a seaward return migration period of mid- to late- June, based on spawning activity in the Miramichi River, NB (Douglas *et al.* 2009) and timing of MRe freshwater residency.

Departure Events

Departure events in the MRe occurred in late July through late September following residency at the Zone 1 estuarine aggregation site. All but one striped bass, which left the system and was possibly captured or predated while outside the MRe, returned to the aggregation site at Albert Bridge by early October. Time of return coincides with the start of migrations to wintering sites by migratory contingents of other striped bass stocks (Mather *et al.* 2010, Pautzke *et al.* 2010, Kneebone *et al.* 2014). Unlike in MRe, however, estuarine egress of these contingents occurred soon after spawning (Douglas *et al.* 2009) and was often associated with summer foraging (Boreman & Lewis 1987, Mather *et al.* 2009). The Mira River estuary departure events appear to be associated only with foraging behaviour.

Striped bass were observed feeding on Atlantic mackerel (*Scomber scombrus* Linnaeus, 1758) at the Albert Bridge aggregation site in late July and early August (CFB, personal observation). Alosid predation is also common throughout the striped bass range (Walter *et al.* 2003) and departure events possibly coincided with juvenile alewife and blueback herring (*Alosa aestivalis* Mitchill, 1815) out-migrations, which typically occur from August through October (Stokesbury & Dadswell 1989, Iafrate & Oliveira 2008, Greene *et al.* 2009). Ng and co-workers (2007) observed that maximum daily movements of striped bass in Mullica River-Great Bay estuary were concentrated around sunset; however, we found that departure events occurred predominantly at night (after twilight hours), which is when juvenile alewife and blueback herring out-migrate to sea (Greene *et al.* 2009). Alternatively, observed preference for nighttime departure and return events may be associated with predator avoidance since Mira Bay is populated with many piscine predators including American bald eagles (Cash *et al.* 1985), osprey, sharks, and seals.

Documented departure events may have been negatively biased due to a lack of receiver coverage in Mira Bay owing to logistical challenges associated with highly mobile sediment upwards of 900 m from the mouth of MRe. The group classified as using the channel leading to the Mira Bay were defined to depart from the system based on a lack of detections in the array for > 24 hours followed by sequential up estuary detections. Thus, departure events for < 24-hour periods are not resolvable by our methods. Given the lack of detections from other nearby receiver arrays striped bass that left the MRe probably remained in the relatively local area of Mira Bay (Bigelow & Schroeder 1953).

Interactions with Other Telemetry Infrastructure

The OTN acoustic telemetry infrastructure in the Canadian Atlantic region with receiver arrays in the Cabot Strait, Bras d'Or Lake, Strait of Canso, and off Halifax, among others in the sGSL and further afield (Bangley *et al.* 2020), would have detected MRe striped bass if they had embarked on northerly or southerly long distance coastal migrations. Similar arrays in the Bay of Fundy and New England coasts often detect migrating striped bass throughout the year as they embark on coastal migrations and exhibit residency in non-natal estuaries (Grothues *et al.* 2009, Mather *et al.* 2010, Kneebone *et al.* 2014, Andrews *et al.* 2017). Throughout our study striped bass tagged in the Mira River estuary remained local freshwater, estuarine, and marine residents.

CONCLUSIONS

Evidence that striped bass stocks at the northern extreme of their range in Nova Scotia have adapted to isolated freshwater watersheds is demonstrated by both past and recent evidence. Anglers in the past have captured numerous record fish in this region from Porters Lake near Halifax north to the Mira estuary (NSDFA 2007, NSDFA 2018, Andrews *et al.* 2019a). Annually there have been reports of large concentrations of juvenile striped bass in local estuaries (Andrews *et al.* 2019a). During exploratory investigations we made before the MRe study we tagged striped bass in the Fourchu area, Cape Breton Island, south of the MRe. Since then, we have had our tags reported by anglers from that area and only that area (CFB, unpublished data). Abundant tagging data from the striped bass stock in the Shubenacadie River, Nova Scotia, indicates fish predominately remain in Minas Basin (Broome 2014). We suggest that striped bass have established isolated, local populations in eastern Nova Scotia like those at the southern extreme of their range (Hess *et al.* 1999, Bjorgo *et al.* 2000, Nelson *et al.* 2010), which complements our understanding of the species biology in the Canadian Maritimes and may be associated with common behavior among stocks near the extents of its range. Critical habitat for establishment of a stock in the Maritimes includes an appropriate wintering site, a spawning site and availability of desired prey. We continue to study this aspect of striped bass biology in Nova Scotia and hope to report further findings in the future.

Acknowledgements We thank G. Nau, J. Beardsall, M. MacDonald, M., G. Lee-Dadswell, A. Spares, M. Buhariwalla, P. Buhariwalla, R. Theriault, R. Madden, M. MacInnis, M. Gregoire, T. Gregoire, L. Boudreau, N. Stewart, R. Buhariwalla, P. Young, E. Stevens, B. Cameron, C. Slater, and M. Gillis for assistance in the field.

J. Broome, D. Bates, M. Brylinsky, and A. Redden provided technical advice and laboratory support. S. Dufault, L. Logan-Chesney, and M. Mihoff helped with data management and analysis. We thank the Ocean Tracking Network for their assistance with detections outside the MRe and providing training opportunities. Nova Scotia Fisheries and Aquaculture, Inland Fisheries Division provided water sampling equipment. Commercial fishermen J. Horne and K. Nichols contributed local fisheries information. Local anglers K. Hutchins, C. Paul, J. Gibbons, S. Jeddore, A. Hunt, and J. Sylvester kept us informed about striped bass fishing in the MRe in the years since our gear was removed. Funding was provided by the Canadian Wildlife Federation, the Ocean Tracking Network, the National Science and Engineering Council through MJWS, the Nova Scotia Freshwater Fisheries Research Cooperative, the Orville Erickson Memorial Scholarship Fund, and the Acadia University Graduate Fund.

REFERENCES

Able, K.W. & Grothues, T.M. (2007). Diversity of estuarine movements of striped bass (*Morone saxatilis*): a synoptic examination of an estuarine system in southern New Jersey. *Fisheries Bulletin* 105: 426-435.

Able, K.W., Grothues, T.M., Turnure, J.T., Byrne, D.M & Clerkin, P. (2012). Distribution, movements, and habitat use of small striped bass (*Morone saxatilis*) across multiple spatial scales. *Fishery Bulletin* 110: 176-192.

Afonso, P., Fontes J., Holland, K.N. & Santos, R.S. (2008). Social status determines behaviour and habitat usage in a temperate parrotfish: implications for marine reserve design. *Marine Ecology Progress Series* 359: 215-227.

Andrews, S.N., Linnansaari, T., Curry, R.A. & Dadswell M.J. (2017). The misunderstood Striped Bass of the Saint John River, New Brunswick: past, present, and future. *North American Journal of Fisheries Management* 37: 235-254.

Andrews, S.N., Wallace, B., Gautreau, M., Linnansaari, T. & Curry, R.A. (2018). Seasonal movements of striped bass *Morone saxatilis* in a large tidal and hydropower regulated river. *Environmental Biology of Fishes* 101: 1549-1558.

Andrews, S.N., Buhariwalla, C.F., Dadswell, M.J., Linnansaari, T. & Curry, R.A. (2019a). Looking for striped bass in Atlantic Canada: The reconciliation of local, scientific, and historical knowledge. *Northeastern Naturalist* 26: 1-30.

Andrews, S.N., Linnansaari, T., Leblanc, T.N., Pavey, N. S. & Curry, R.A. (2019b). Interannual variation in spawning success of striped bass

(*Morone saxatilis*) in the Saint John River, NB. *River Research and Applications* 36: 13-24.

Andrews, S.N., Buhariwalla, C.F., Fleet-Purdy, B., Dadswell, M.J., Linnansaari, T. & Curry, R.A. (2019c). Left out in the cold: the understudied overwintering ecology of striped bass in Canada. *Environmental Biology of Fishes* 102: 499-518.

Andrews, S.N., Linnansaari, T., Curry, R.A., LeBlanc, N.M. & Pavey, S.A. (2020). Winter ecology of striped bass (*Morone saxatilis*) near the northern limit of distribution in the Saint John River, New Brunswick. *Environmental Biology of Fishes* 103: 1343-1358.

ASMFC (Atlantic States Marine Fisheries Commission). 2016. ASMFC Atlantic striped bass stock assessment update 2016. Arlington, VA. 101 pp.

Bangley, C.W., Whoriskey, F.G., Young, J.M. & Ogbum M.B. (2020). Networked animal telemetry in the northwest Atlantic and Caribbean waters. *Marine and Coastal Fisheries; Dynamics, Management, and Ecosystem Science* 12: 339-347.

Bigelow, H.B. & Schroeder, W.C. (1953). Fishes of the Gulf of Maine. *Fishery Bulletin of the Fish and Wildlife Service* 53. 577 p.

Bjorgo, K.A., Isely, J.J. & Thomason, C.S. (2000). Seasonal movement and habitat use by striped bass in the Combahee River, South Carolina. *Transactions of the American Fisheries Society* 129: 1281-1287.

Boreman, J. & Lewis, R.R. (1987). Atlantic coastal migration of striped bass. *American Fisheries Society Symposium* 1: 331-339.

Bousfield, E.L. & Thomas, M.H.L. (1975). Postglacial changes in distribution of littoral marine invertebrates in the Canadian Atlantic region. *Proceedings of the Nova Scotian Institute of Science* (Supplement) 3: 47-60.

Bradford, R.G., & Chaput, G.J. (1996). The status of striped bass (*Morone saxatilis*) in the southern Gulf of St. Lawrence in 1995. Department of Fisheries and Oceans, Atlantic Fisheries Research Document 96/62, Ottawa, ON.

Bradford, R.G., Tremblay, E. & Chaput, G.J. (1998). Winter distribution of striped bass (*Morone saxatilis*) and associated environmental conditions in Kouchibouguac National Park during 1996-1997. Ecosystem Monitoring and Data Report 0003. Parks Canada, Ottawa, ON.

Bradford, R.G., LeBlanc, P. & Bentzen, P. (2012). Update status report on Bay of Fundy striped bass (*Morone saxatilis*). Canadian Scientific Advisory Secretariat Research Document 2012/021, Ottawa, ON.

Broome, J.E. (2014). Population characteristics of striped bass (*Morone saxatilis*, Walbaum, 1792) in Minas Basin and patterns of acoustically detected movements within Minas Passage. MSc. Thesis, Acadia University, Wolfville, NS.

Buhariwalla, C.F., MacMillan, J.L., Gregoire, M.J., Dadswell, M.J. & Stokesbury, M.J.W. (2016). Population characteristics of striped bass killed by cold shock during winter shutdown of a power plant in Nova Scotia. *Northeastern Naturalist* 23: 163-173.

Cash, K.J., Austin-Smith, P.J., Banks, D., Harris, D. & Smith, P.C. (1985). Food remains from bald eagle nest sites on Cape Breton Island, Nova Scotia. *The Journal of Wildlife Management* 49: 223-225.

Chapman, B.B., Skov, C., Hulthén, K., Brodersen, J., Nilsson, P.A., Hansson, L.A. & Brönmark, C. (2012). Partial migration in fishes: definitions, methodologies, and taxonomic distribution. *Journal of Fish Biology* 81: 479-499.

Clark, J. (1968). Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. *Transactions of the American Fisheries Society* 97: 320-343.

Cooke, S.J., Iverson S.J., Stokesbury, M.J.W., Hinch, S.G., Fisk, A.T., VanderZwaag, D.L., Apostle, R. & Whoriskey, R.F. (2011). Ocean Tracking Network Canada: A network approach to addressing critical issues in fisheries and resource management with implications for ocean governance. *Fisheries* 36: 583-592.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). (2004). COSEWIC assessment and status report on the striped bass *Morone saxatilis* in Canada. Ottawa, ON.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). (2012). COSEWIC assessment and status report on the striped bass *Morone saxatilis* in Canada. Ottawa, ON.

Coutant, C.C. (1985). Striped bass, temperature, and dissolved oxygen: A speculative hypothesis for environmental risk. *Transactions of the American Fisheries Society* 114: 31-61.

Crossin, G.T., Hatcher, B.G., Denny, S., Whoriskey, K., Orr, M., Penney, A. & Whoriskey, F.G. (2016). Condition-dependent migratory behaviour of endangered Atlantic salmon smolts moving through an inland sea. *Conservation Physiology* 4(1):cow018. doi: 10.1093/conphys/cow018.

Dadswell, M.J., Melvin, G.D., Williams, P.J. & Themelis, D.E. (1987). Influences of origin, life history and chance on the Atlantic coast migration of American shad. *American Fisheries Society Symposium* 1: 313-330.

Dadswell, M.J. & Rulifson, R.A. (1994). Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. *Biological Journal of the Linnaean Society* 51: 93-113.

Dadswell, M.J., Spares, A.D., McLean, M.F., Harris P.J. & Rulifson, R.A. (2018). Long-term impact of a tidal, hydroelectric propeller turbine on the populations of three anadromous fish species. *Journal of Fish Biology* 93: 192-206.

Dadswell, M.J., Spares, A.D., Reader, J.M. & Stokesbury M.J.W. (2010). The North Atlantic sub-polar gyre and the marine migration of Atlantic Salmon: the "Merry-Go-Round" hypothesis. *Journal of Fish Biology* 77: 435-467.

DeVries, D.R. & Frie, R.V. (1996). Determination of age and growth. In. Fisheries Techniques (eds.) B. R. Murphy & Willis D.W. 2nd Edition. (p. 483-512. American Fisheries Society Bethesda, Maryland, USA.

DFO (Department of Fisheries and Oceans Canada). (2017). Spawner abundance and biological characteristics of striped bass (*Morone saxatilis*) in the southern Gulf of St. Lawrence in 2016. Department of Fisheries and Oceans. Canadian Science Advisory Secretariat Science Response 2017/012.

Douglas, S.G., Bradford, R.G. & Chaput, G. (2003). Assessment of striped bass (*Morone saxatilis*) in the Maritime Provinces in the context of species at risk. Department of Fisheries and Oceans. Canadian Science Advisory Secretariat Research Document 2003/008, Ottawa, ON.

Douglas, S.G. & Chaput, G. (2011). Information on the striped bass (*Morone saxatilis*) population of the southern Gulf of St. Lawrence relevant to the development of a 2nd COSEWIC status report for the species. Department of Fisheries and Oceans. Canadian Scientific Advisory Secretariat Research Document 2011/098.

Douglas, S.G., Chaput, G. & Caissie, D. (2006). Assessment of status and recovery potential for striped bass (*Morone saxatilis*) in the southern Gulf of St. Lawrence. *Department of Fisheries and Oceans. Canadian Science Advisory Secretariat Research Document* 2006/41.

Douglas, S.G., Chaput, G. Hayward, J. & Sheasgreen, J. (2009). Prespawning, spawning, and postspawning behavior of striped bass in the Miramichi River. *Transactions of the American Fisheries Society* 138: 121-134.

Duston, J., Mauriquez-Hernanadez, J., MacInnis, G.M. Reesor, C.M. & Astatkie, T. (2018). Striped bass early life history in the macrotidal Shubenacadie River. *Transactions of the American Fisheries Society* 147: 919-938.

Field, J.D. (1997). Atlantic Striped Bass management: where did we go right? *Fisheries* 22: 6-8.

Gahagan, B.I., Fox, B.A. & Secor, D.H. (2015). Partial migration of striped bass: revisiting the contingent hypothesis. *Marine Ecology Progress Series* 525: 185-197.

Grant, D.R. (1970). Recent coastal submergence of the Maritime Provinces, Canada. *Canadian Journal of Earth Sciences* 7: 676-689.

Greene, K.E., Zimmerman, J.L., Laney, R.W. & Thomas-Blate, J.C. (2009). Atlantic coast diadromous fish habitat: a review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission Habitat Management Series No. 9, Washington, D.C., USA.

Grolemund, G. & Wickham, H. (2011). Dates and times made easy with lubridate. *Journal of Statistical Software* 40: 1-25.

Grothues, T.M., Able, K.W., Carter, J. & Arienti, T.W. (2009). Migration patterns of striped bass through non-natal estuaries of the U.S. Atlantic coast. *American Fisheries Society Symposium* 69: 135-150.

Haeseker, S.L., Carmichael, J.T. & Hightower, J.E. (1996). Summer distribution and condition of Striped Bass within Albemarle Sound, North Carolina. *Transactions of the American Fisheries Society* 125: 690-704.

Hansen, L.P. & Jonsson, B. (1991). Evidence of a genetic component in the seasonal return pattern of Atlantic salmon, *Salmo salar* L. *Journal of Fish Biology* 31: 251-258.

Harding, J.M. & Mann, R. (2003). Influence of habitat on diet and distribution of striped bass (*Morone saxatilis*) in a temperate estuary. *Bulletin of Marine Science* 72: 841-851.

Hartman, K.J. & Brandt, S.B. (1995). Comparative energetics and the development of bioenergetics models for sympatric estuarine piscivores. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 1647-1666.

Hess, B.J., Jackson, C. & Jennings, C.A. (1999). Use of cool-water springs as thermal refuge by striped bass in the Ogeechee River, Georgia. *Georgia Journal of Science* 57: 123-130.

Hurst, T.P. & Conover, D.O. (2002). Effects of temperature and salinity on survival of young-of-the-year Hudson River striped bass (*Morone saxatilis*): Implications for optimal overwintering habitats. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 787-795.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F, Mills, J.E., Felmming, F. & Whoriskey, F.G. (2015). Aquatic animal telemetry: a panoramic window into the underwater world. *Science* 348: 1221-1232.

Iafrate, J. & Oliveira, K. (2008). Factors affecting migration patterns of juvenile river herring in a coastal Massachusetts stream. *Environmental Biology of Fishes* 81: 101-110.

Kessel, S.T., Hussey, N.E., Crawford, R.E., Yukowski, D.J., O'Neill, C.V. & Fisk, A.T. (2016). Distinct patterns of Arctic cod (*Boreogadus saida*) presence and absence in a shallow high Arctic embayment, revealed across open-water and ice-covered periods through acoustic telemetry. *Polar Biology* 39: 1057-1068.

Keyser, F.M., Broome, J.E., Bradford, R.G., Sanderson, B. & Redden, A.M. (2016). Winter presence and temperature related diel vertical migration of striped bass (*Morone saxatilis*) in an extreme high-flow passage in the inner Bay of Fundy. *Canadian Journal of Fisheries and Aquatic Sciences* 73: 1777-1786.

Kneebone, J., Hoffman, W.S., Dean, M.J., Fox, D.A. & Armstrong, M.P. (2014). Movement patterns and stock composition of adult striped bass tagged in Massachusetts coastal waters. *Transactions of the American Fisheries Society* 143: 1115-1129.

LeBlanc, N.M., Gahagan, B.I., Andrews, S.N., Avery, T.S., Puncher, G.N., Reading, B.J., Buhariwalla, C.F., Curry, R.A., Whiteley, A.R. & Pavey, A.S. (2020). Genomic structure of striped bass (*Morone saxatilus*) from the Gulf of St. Lawrence to the Cape Fear River. *Evolutionary Applications* 13: 1468-1486.

Lemm, C.A. (1993). Evaluation of five anaesthetics on striped bass. U.S Fish and Wildlife Service Resource Publication 196.

Little, M.J. (1995). A report on the historic spawning grounds of the striped bass, "*Morone saxatilis*". *Maine Naturalist* 3: 107-113.

MacInnis, G.M. (2012). Spatio-temporal distribution of eggs and age-0 striped bass (*Morone saxatilis*) in the Shubenacadie River estuary. M.Sc. Thesis, Dalhousie University, Halifax, NS.

Magnin, É. & Beaulieu, G. (1967). Le bar, *Roccus saxatilis* (Walbaum), du Flueve Saint-Laurent. *Naturaliste Canadienne* 94: 539-555.

Mather, M.E., Finn, J.T. Ferry, K.H., Deegan, L.A. & Nelson G.A. (2009). Use of non-natal estuaries by migratory striped bass (*Morone saxatilis*) in summer. *Fisheries Bulletin* 107: 329-338.

Mather, M.E., Finn, J.T., Pautzke, S.M., Fox, D., Savoy, T., Brundage III, H.M., Deegan, L.A. & Muth, R.M. (2010). Diversity in destinations, routes, and timing of small adult and sub-adult striped bass *Morone saxatilis* on their southward autumn migration. *Journal of Fish Biology* 77: 2326-2337.

McLean, M.F., Simpfendorfer, C.A., Heupel, M.R., Dadswell, M.J. & Stokesbury, M.J.W. (2014). Diversity of behavioural patterns displayed by a summer feeding aggregation of Atlantic sturgeon in the intertidal region of Minas Basin, Bay of Fundy, Canada. *Marine Ecology Progress Series* 496: 59-69.

Merriman, D. (1941). Studies on the striped bass of the Atlantic coast. *U.S. Fish and Wildlife Service Fishery Bulletin*. 50: 1-77.

Nelson, G.A., Armstrong, M.P., Stritzel-Thomson, J. & Friedland K.D. (2010). Thermal habitat of striped bass (*Morone saxatilis*) in coastal waters of northern Massachusetts, USA, during summer. *Fisheries Oceanography* 19: 370-381.

Ng, C.L., Able, K.W. & Grothues, T.M. (2007). Habitat use, site fidelity, and movement of adult striped bass in a southern New Jersey estuary based on mobile acoustic telemetry. *Transactions of the American Fisheries Society* 136: 1344-1355.

NRCC (National Research Council of Canada). (2018). Sunrise/sunset calculator.
https://www.nrc-cnrc.gc.ca/eng/services/sunrise/advanced.html

NSDOE (Nova Scotia Department of the Environment). (1976). Report on Mira River water quality for Nova Scotia Department of Environment. Prepared by C.A. Campbell Consultants Ltd., Sydney, NS.

NSDFA (Nova Scotia Department of Fisheries and Aquaculture). (2007). Nova Scotia anglers' handbook and 2007 summary of regulations. Pictou, NS.

NSDFA (Nova Scotia Department of Fisheries and Aquaculture). (2018). Nova Scotia Anglers' Handbook and 2018 summary of regulations. Pictou, NS.

O'Dor, R.K., & Stokesbury M.J.W. (2009). The ocean tracking network-adding animal movements to the global ocean observing system. In. Tagging and tracking marine animals with electronic devices. (eds.). Nielsen, J.L., Arrizabalga, H. Fragoso, H., Hobday, A., Lutcavage, M.L. & Sibert, J. (p. 91-100). Springer, Dordrecht.

Ogle, D.H. (2014). FSA: Fisheries stock analysis. R package version 0.4.3.

Paramore, L.M. & Rulifson R.A. (2001). Dorsal coloration as an indicator of different life history patterns for striped bass within a single watershed of Atlantic Canada. *Transactions of the American Fisheries Society* 130: 663-674.

Pautzke, S. M., Mather, M.E., Finn, J.T., Deegan, L.A. & Muth R.M. (2010). Seasonal use of a New England estuary by foraging contingents of migratory striped bass. *Transactions of the American Fisheries Society* 139: 257-269.

Pewsey, A., Neuhäuser, M. & Ruxton G.D. (2013). Circular statistics in R. Oxford University Press. Oxford, UK.

Pohlert, T. (2014). The pairwise multiple comparison of mean ranks package (PMCMR). R Package: http://CRAN.R-project.org/package=PMCMR.

R Core Team. (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. URL:http:/www.R-project.org/.

Richards, R.A. & Rago, P.J. (1999). A case history of effective fishery management: Chesapeake Bay striped bass. *North American Journal of Fisheries Management* 19: 356-375.

Ricker, W.E. (1975). Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada* 191.

Robichaud-LeBlanc, K.A., Courtenay, S.C. & Locke A. (1996). Spawning and early life history of a northern population of striped bass (*Morone saxatilis*) in the Miramichi River estuary, Gulf of St. Lawrence. *Canadian Journal of Zoology* 74: 1645-1655.

Robitaille, J.M., Bérubé, M., Gosselin, A., Baril, M., Beauchamp, J., Boucher, J., Dionne, M., Legault, M., Mailhot, Y., Ouellet, B., Sirois, P., Tremblay, S., Trencia, G., Verreault, G. & Villeneuve, D. (2011). Recovery strategy for the striped bass (*Morone saxatilis*), St. Lawrence estuary population, Canada. Species at Risk Act Recovery Strategy Series. Ottawa: Fisheries and Oceans Canada.

Rulifson, R.A. & Dadswell, M.J. (1995). Life history and population characteristics of striped bass in Atlantic Canada. *Transactions of the American Fisheries Society* 124: 477-507.

Rulifson, R.A., McKenna, S.A. & Dadswell, M.J. (2008). Intertidal habitat use, population characteristics, movement, and exploitation of striped bass in the inner Bay of Fundy, Canada. *Transactions of the American Fisheries Society* 137: 23-32.

Rulifson, R.A. & Tull, K.A. (1998). Striped bass spawning in a tidal river: the Shubenacadie estuary, Atlantic Canada. *Transactions of the American Fisheries Society* 128: 613-624.

Scott, W.B. & Scott, M.G. (1988). Atlantic Fishes of Canada. University of Toronto Press, Toronto, ON.

Secor, D.H. (1999). Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fisheries Research* 43: 13-34.

Secor, D.H., O'Brien, M.H.P., Gahagan, B.I., Watterson, J.C. & Fox, D.A. (2020). Differential migration in Chesapeake Bay striped bass. *PLoS ONE* 15:e023303.

Secor, D.H. & Piccoli, P.M. (1996). Age- and sex-dependent migrations of striped bass in the Hudson River as determined by chemical microanalysis of otoliths. *Estuaries* 19: 778-793.

Secor, D.H. & Piccoli, P.M. (2007). Oceanic migration rates of upper Chesapeake Bay striped bass (*Morone saxatilis*), determined by otolith microchemical analysis. *Fisheries Bulletin* 105: 62-73.

Setzler, E.M., Boynton, W., Wood, K., Zion, H., Lubbers, L., Mountford, N., Frere, P., Tucker, L. & Mihursky, J. (1980). Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). National Oceanic and Atmospheric Administration Technical Report. National Marine Fisheries Service Circular 433, Silver Spring, Maryland, USA.

Setzler-Hamilton, E.M. & Hall Jr., L. (1991). Striped bass *Morone saxatilis*. In. Habitat requirements for Chesapeake Bay living resources. (eds.). Fuderburk, S.I., Jordan, S.J., Mihursky, J.A. & Riley, D. 2nd edition. (p.13-31) Habitat Objectives Workgroup, Living Resources Subcommittee, Chesapeake Research Consortium, Inc., Solomons, Maryland, USA.

Sipfendorfer, C.A., Huveneers, C., Steckenreuter, A., Tattersall, K., Hoenner, X., Harcourt, R. & Heupel, M.R. (2015). Ghosts in the data: false detections in VEMCO pulse position modulation acoustic telemetry monitoring equipment. *Animal Biotelemetry* 3: 55.

Stephenson, A. G. (2016). Harmonic analysis of tides using TideHarmonics. R package. https://CRAN.R-project.org/package=TideHarmonics.

Stokesbury, K.D.E. & Dadswell, M.J. (1989). Seaward migration of juveniles of three herring species, *Alosa*, from an estuary in the Annapolis River, Nova Scotia. *Canadian Field Naturalist* 103: 388-393.

Trent, L. & Hassler, W.W. (1968). Gill net selection, migration, size and age composition, sex ration, harvest efficiency, and management of striped bass in the Roanoke River, North Carolina. *Chesapeake Science* 9: 217-232.

Waldman, J.R., Dunning, D.J., Ross, Q.E., & Mattson, M.T. (1990). Range dynamics of Hudson River striped bass along the Atlantic coast. *Transactions of the American Fisheries Society* 119: 910-919.

Walter, J.F. III., Overton, A.S., Ferry, K.H. & Mather, M.E. (2003). Atlantic coast feeding habits of striped bass: A synthesis supporting coast-wide understanding of trophic biology. *Fisheries Management and Ecology* 10: 349-360.

White, E., Mihoff, M., Jones, B., Bajona, L. & Halfyard, E. (2014). White-Mihoff false filtering tool. Ocean Tracking Network. Halifax, NS http://members.devel.oceantrack.org/data/otn-tool-box.

Wickham, H. (2009). Ggplot2: elegant graphics for data analysis [online]. Springer, New York. Available from https://cran.r-project.org/web/packages/ggplot2/index.html.

Wickham, H. & Francois, R. (2015). dplyr: A grammar of data manipulation [online]. R package version 0.4.1.
Available from https://cran.r-project.org/web/packages/dplyr/index.

Wickham, H. & Grolemund, G. (2017). R for data science: import, tidy, transform visualize, and model data. O'Reilly Media Inc, Sebastopol, California, USA.

Wilkerson, M.L. & Fisher, W.L. (1997). Striped bass distribution, movements, and site fidelity in Robert S. Kerr Reservoir, Oklahoma. *North American Journal of Fisheries Management* 17: 677-686.

Williams, K. & Waldman, J. (2010). Aspects of the wintering biology of striped bass at a power plant discharge. *Northeastern Naturalist* 17: 373-386.

Wingate, R.L. & Secor, D H. (2007). Intercept telemetry of the Hudson River striped bass resident contingent: migration and homing patterns. *Transactions of the American Fisheries Society* 136: 95-104.

Wingate, R.L., Secor, D.H. & Kraus, R.T. (2011). Seasonal patterns of movement and residency by striped bass within a sub-estuary of the Chesapeake Bay. *Transactions of the American Fisheries Society* 140: 1441-1450.

Zar, J.H. (2010). Biostatistical Analysis: Fifth Edition. Prentice-Hall, New York, USA.