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Landlocked Atlantic salmon: movements to sea by a putative freshwater life history form

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Abstract

Certain populations of Atlantic salmon (*Salmo salar*) have become landlocked, and live their entire life history out in freshwater. On the Magaguadavic River, New Brunswick, Canada, hatchery and wild origin landlocked salmon were detected moving downstream towards the ocean, and subsequently back upstream in the river. High levels of strontium, indicative of ocean residence, were found in the scales of these fish. In 2002 and 2003, 23 and 13 landlocked salmon, respectively, from this river were fitted with acoustic tags, and their movements in the lower river and adjacent coastal area were monitored. Some fish covered long distances, eventually moving beyond our tracking array. Others remained in coastal waters in close proximity to the river and its estuary. Two fish that returned early to the river were infested with sea lice, and were detected in areas close to commercial salmon farms.

Introduction

Atlantic salmon exist in both anadromous and non-anadromous forms (Power, 1958; Berg, 1985). Anadromous salmon typically migrate to sea as juveniles (smolt) and return as adults to their natal stream to spawn. Non-anadromous or resident (landlocked) salmon spend their entire life cycle in freshwater, typically using lakes in the watershed as feeding areas for larger fish. Landlocked parr, similar to the anadromous form, inhabit riffle areas. The occurrence of anadromous and landlocked Atlantic salmon is widespread in eastern North America (Scott and Crossman, 1964). Often the two forms are sympatric within a river system. New Brunswick's Magaguadavic River has both anadromous and landlocked forms of Atlantic salmon. In this river, the history of the landlocked salmon population was uncertain prior to the establishment of a hatchery stocking program. Stocking of landlocked salmon into lakes in the Magaguadavic watershed by federal and provincial government agencies began in 1980, and continues now. Some of these fish now reproduce naturally in the river. The history of the anadromous Atlantic salmon has been well documented for the river (Martin, 1984; Carr, 1995; Carr *et al*., 1997). However, little information is available on the non-anadromous form other than stocking records.

An anadromous salmon monitoring program detected landlocked salmon moving downstream towards the ocean, and subsequently back upstream in the river. It was not known if the fish took up residency in seawater, and if so, how far out to sea they ventured. We also did not know if these were passive movements, driven by spring freshets, or if the fish were showing active migratory tendencies.

Strontium (Sr) has been measured in scales and otoliths by various researchers to document fish movements between freshwater and marine environments (Bagenal *et al*., 1973; Kalish, 1990; Coutant and Chen, 1993; Halden *et al*., 1995; Babaluk *et al*., 1997; Eek and Bohlin, 1997). As fish grow, their scales develop concentrations of trace elements (i.e. Sr) in the calcified matrix that are proportional to those in the environment in which they live. Since Sr concentration is enriched in seawater, a high Sr level (as measured by the standardized Sr/Ca ratio) in some portions of the scales would indicate periods of life spent in seawater. The objectives of this study were: (1) to determine whether the landlocked salmon did move into the marine environment by assessing Sr concentrations in their scales, (2) to determine whether the downstream movement patterns of landlocked salmon are similar to those of anadromous salmon smolts, and (3) to assess marine survival and movement patterns of downstream moving landlocked salmon by acoustically tagging and tracking them through the lower river and out into the surrounding marine environment.

Materials and methods

Study area

The Magaguadavic River is the sixth largest river in New Brunswick. It originates in Magaguadavic Lake in the southwestern part of the province and flows southeasterly 97 km to Passamaquoddy Bay (Fig. 1). There are 103 named tributaries and more than 55 lakes within a drainage area of 1812 km^2. A 13.4 m high dam (built in 1903) located at the head of the tide is equipped with Francis runner-type turbines that generate about 3.7 megawatts of power. A pool and weir fishway bypasses the dam for upstream fish passage. All fish ascending the river from seawater must pass through a collection trap in the fishway. A sluiceway intended for downstream fish passage is situated adjacent to the penstock. The Magaguadavic River drainage supports a sport fishery for landlocked Atlantic salmon, brook trout (*Salvelinus fontinalis*), and introduced smallmouth bass (*Micropterus dolomieui*). The sport fishery for the anadromous salmon run has been closed since 1992 as a result of precipitous declines in the run.

Landlocked salmon were first stocked into Magaguadavic Lake in 1980. From 1985 to 1997, progeny from wild origin broodstock from four New Brunswick lakes (Skiff, Oromocto, Grand, Chamcook) and from Grand Lake, Maine were released into the river. Since 1998, all source broodstock for the stocking program have originated from lakes within the Magaguadavic drainage. Landlocked salmon stocked into the river are all fin clipped to permit identification. Most hatchery fish are released as one year olds, and stocking densities generally range from 1000 to 8000 fish annually.

Identification of landlocked salmon

Salmon were classified as anadromous or landlocked on the basis of fin clips, size, and scale analysis. Stocked hatchery landlocked salmon often have fin clips corresponding to release years and locations. Fork length was recorded to the nearest mm, and a sample of scales was taken to identify the fish. Freshwater ages were determined from circuli patterns on the scales. All Magaguadavic origin wild anadromous salmon smolt move to sea at 2 to 3 years of age, and their fork lengths range from 13 to 25 cm. Wild landlocked salmon leaving the river have been 3 to 7 years of age, with sizes ranging from 31 to 58 cm. Hatchery origin landlocked salmon were stocked as one-year-old at sizes generally greater than 25 cm. Two-year-old hatchery fish have been documented leaving the river at sizes greater than 30 cm.

Strontium Analysis

The analysis of Sr was done using a wavelength dispersive X-ray electron microprobe (WD-EM at the University of New Brunswick, Canada). We analysed scales collected from 34 landlocked salmon returning to freshwater from the sea that were captured at the head of tide fishway trap (13 from 1996, 2 from 1997, 12 from 1998, and 7 from 1999). The scales were embedded in an epoxy matrix (Epofix©) and a transverse cut was made along the long axis of the scale, through the focus, using a steel blade microtome. The smooth surface necessary for the use of WD-EM was attained with a finishing cut using a glass-knife ultramicrotome and the finished blocks were carbon-coated.

We analysed the first five contiguous circuli and 15 additional points were sampled at every other circulus, when possible, covering a region corresponding to approximately the 35 last-laid circuli. Since between 8 and 12 circuli are formed each year in the case of the Atlantic salmon (Summerfelt and Hall, 1987), we investigated the past three or four years of these fish, at a one or two month time resolution. Further details on the methods are given in Courtemanche (2003).

measured, and a sample of scales and fin tissue was taken. Salmon were kept for tagging if they exhibited no external deformities or injuries. All other fish were released downstream of the collection device.

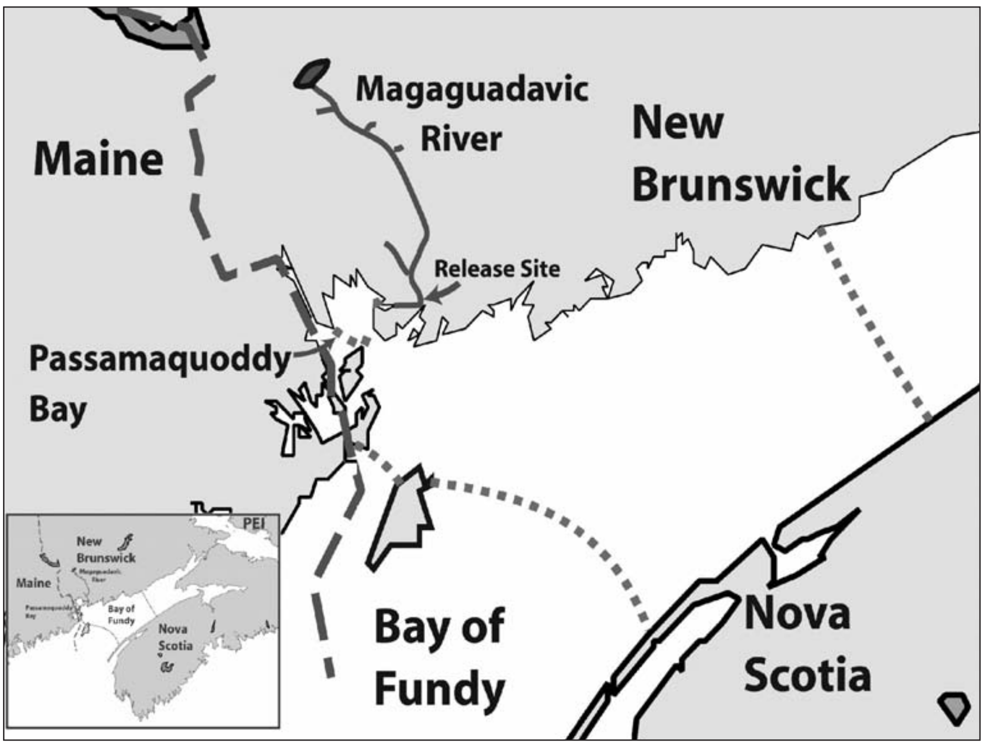

Fig. 1 – Map of study area showing the release site for tagged salmon and the three tracking zones: Magaguadavic River release site to it's confluence with the Passamaquoddy Bay (Zone 1), Passamaquoddy Bay (Zone 2), and the Bay of Fundy (Zone 3). The tracking array in the bays are shown by small squares. The international border is shown by a dashed line.

Tagging Program

Downstream moving landlocked salmon were captured in a smolt counting fence trap (operational from 18 April to 14 June 2002, and from 30 April to 17 June 2003) situated in a bypass stream below the downstream fish passage facility. The trap was monitored daily and fish were classified as landlocked salmon based on size, fin clips, and scale analysis. All fish captured were

Tagging Procedures

V16-4H-R04K coded ultrasonic pingers (65 mm length x 15 mm diameter; weight 26 g, produced by Vemco Limited, Shad Bay, Nova Scotia) were used to tag landlocked salmon. Pingers had a frequency of 69 kHz, minimum and maximum off delays of 10-35 seconds, and an expected life of 366 days.

Pingers were surgically implanted in the peritoneal cavity of the fish. The anaesthetized (using clove oil [40 mgl^{-1}]) salmon were placed ventral side up in a V-shaped trough with moist paper toweling for support. Germex was used to sterilize all surgical tools, sutures, and pingers. Furacin was used to clean the ventral surface of the fish prior to making a 2 cm mid-ventral incision beginning 1 cm anterior to the pelvic fins. The pinger was inserted into the peritoneal cavity under the incision. Three to four sutures (4-0 Ethilon black monofilament nylon with FS-2 circular cutting needle) were applied to close the incision and a tissue cement (Vetbond) was used to seal the incision and stitches. Furacin was sprayed on the closed incision. Fish recovered in less than 10 minutes from the anesthesia and were able to quickly equilibrate after pinger insertion. The salmon were monitored in an oxygenated tank for 24 hours before being released. No post tagging mortalities occurred prior to release.

Releases

In 2002, a total of 23 landlocked salmon were tagged and released from 9 May to 14 June 2002. In 2003, thirteen landlocked salmon were tagged and released from 29 May to 17 June. All fish were released in the Magaguadavic River estuary, situated 500 m below head of tide. Tagged salmon were released between 06:00 and 20:00 hours. No significant differences were observed among fork length or tag to body weight ratios of tagged fish among the release dates and times in each of the years ($P>0.05$).

Tracking

Movements of tagged fish were monitored by positioning submersible receivers (VEMCO VR2-Monitor), each having a built-in omni directional hydrophone with data logging components programmed to decode and identify individual tagged fish at various points (Fig. 1). Weekly active searches for tagged fish were performed (9 May to 11 September in 2002, and on 14 August and 12 September 2003) using a boat equipped with a land-based receiver (VEMCO VR60) having either directional (VEMCO V10) or omni directional (VEMCO VH65) hydrophones. The marine arrays placed in the Bay of Fundy were part of a joint tracking program between the Department of Fisheries and Oceans and the Atlantic Salmon Federation. There were no tracking arrays in the Bay of Fundy in 2003.

Due to the small sample sizes, statistical comparisons were made by non-parametric tests (χ^2, Mann-Whitney, Kruskal-Wallis). The SAS generalized linear model (GLM) was used for comparison of samples of unequal size. The Pearson correlation coefficient was used to test the strength of association of environmental parameters between fish captures.

Results

High levels of strontium were detected in 91% (31) of the landlocked salmon scales analysed (Fig. 2). Only 9% (3) fish had no strontium in their scales (Fig. 2). The mean fork length of the 34 fish sampled was 44.2±4.9 cm. The mean fork lengths of the fish with scales with and without strontium were 46.3±4.3 cm and 44.0±5.0 cm, respectively. Ages of the fish ranged from two to five years. There was no significant difference in fork length or ages between the salmon with scales showing the presence or absence of strontium ($P>0.05$).

A total of 62 landlocked salmon were captured moving seaward during the anadromous smolt run in 2002, and their mean fork length was 35.7±5.2 cm. Most of the 2002 landlocks (75%) and anadromous smolt (89%) were captured over a 29-day period when water temperatures and water discharges averaged 13.9±2.2 °C and 19.7±10.3 m^3s^{-1}, respectively (Fig. 3a). A total of 21 landlocked salmon were captured moving seaward during the anadromous smolt run in 2003, and their mean fork length was 42.2±5.67 cm. Most of the 2003 landlocks (76%) and anadromous smolt (68%) were captured over a 7-day period when water temperatures and water discharges averaged 13.7±0.69 °C and 30.9±6.50 m^3s^{-1}, respectively (Fig. 3). There was no significant correlation between numbers of salmon captured and any of the environmental parameters (water temperature and discharge) measured in each of the years (P>0.05).

The mean fork length and tag to body weight ratio of tagged salmon in 2002 was 40.7±4.5 cm and 4.7±1.0 %, respectively (Table 1). Their ages ranged from 2 to 5 years (Table 1). The mean fork length and tag to body weight ratio of tagged salmon in 2003 was 43.8±5.4 cm and 4.1±1.3%, respectively (Table 1). Their ages ranged from 3 to 7 years (Table 1). No significant differences were observed in fork lengths, tag to body weight ratios, or ages between wild and hatchery landlocked salmon in each of the years (P>0.05, see Table 1). However, fork lengths of the tagged salmon in 2003 were slightly larger than the tagged fish in 2002 (P<0.05). No differences were found in tag to body weight ratios between the two years (P>0.05).

Three (13%) and one (8%) of the tagged salmon did not leave the seawater section of the Magaguadavic River in 2002 and 2003, respectively (zone 1, see Fig. 1). Those fish moved 8 km from the release site to the mouth of the river where they resided (within a 1 km section inside river mouth) throughout the study. A total of 14 (61%) and 9 (69%) of the tagged fish moved into Passamaquoddy Bay in 2002 and 2003, respectively (zone 2, Fig. 1). Five salmon tracked in 2002 were detected on receivers in the Bay of Fundy (zone 3, Fig. 1). No receivers were positioned in the Bay of Fundy in 2003.

It took the tagged salmon from 1 to 22 days to reach the mouth of the river (8 km) in 2002, significantly longer than the 1 to 4 days it took for the tagged fish in 2003 to cover the same distance (P<0.05, see Table 2). The sizes of the tagged salmon tracked to the mouth of the river in 2003 were significantly larger than the fish tracked in 2002 (P<0.05, see Table 2). The tag to body weight ratio for the same group of fish in 2003 was lower than those in 2002 (P<0.05, see Table 2). The ultimate destination of individual fish did not significantly influence the time taken to reach the river's mouth within each year (P>0.05, see Table 2). There was no difference between years in the fraction of tagged fish moving out of the river and into the bay (P>0.05).

The final positions for the 14 tagged fish that left the river in 2002 was as follows: six signals were last recorded in Passamaquoddy Bay, four signals were last detected in the anadromous salmon smolt migration route between Grand Manan NB, and Nova Scotia, and four fish had returned to the river. The latter group spent from 1 to 31 days at sea before returning to the river. Of the fish returning to the river, two were recaptured in the fishway trap at head of tide 45 and 55 days after initial release. One of the recaptured fish had travelled to the inner Bay of Fundy, more than 150 km from the initial point of release (see inner bay arrays, Fig. 1). Both recaptures had heavy sea lice (*Lepeophtheirus salmonis*) infestations and extensive external damage along the head, typical of sea lice attachment. The fish had increased in length by 1.4 and 1.7 cm respectively, during their residence at sea.

The final positions for the tagged salmon in 2003 was as follows: four signals were last detected on receivers in Passamaquoddy Bay, five signals were never detected after the fish left the Magaguadavic River, and the signal from one fish remained near the mouth of the Magaguadavic River. It is unknown whether any tagged fish left Passamaquoddy Bay since no receivers were positioned in the Bay of Fundy in 2003. Although no tagged fish returned to the river in 2003, there was no significant difference in fractions of active tracked fish returning to freshwater (9% in 2002, 0% in 2003) between the two years (P>0.05).

Six (26%) and three (23%) of the tagged fish were suspected to have died within 3 km downstream of the release site in 2002 and 2003, respectively since their signals were either lost or tag positions remained stationary within two days after release. The tag to weight ratios for the six (2002) and three (2003) lost signals was 4.0±1.3 and 4.4±0.6%, respectively (Table 2). There was no significant difference in the fractions of signals lost between years (P>0.05). The pooled data (2002 and 2003) showed no significant difference in both tag to weight ratios and fish sizes for lost signals and fish tracked in zones 1 to 3 (P>0.05, see Table 2).

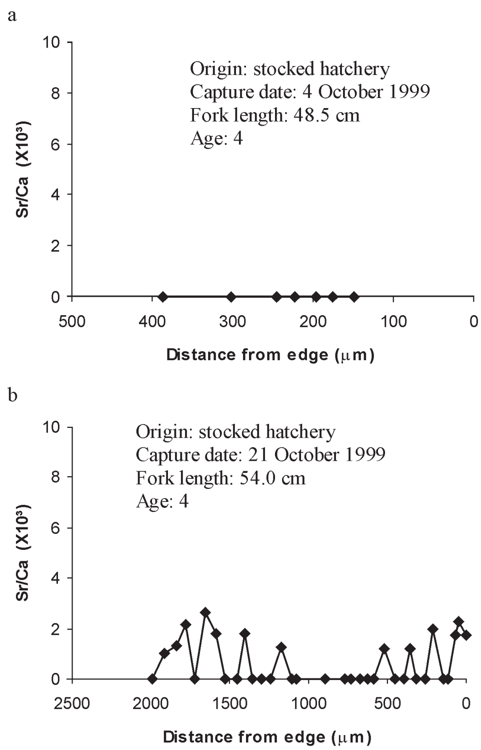

Fig. 2 – Representative Sr/Ca analysis from two different fish that had returned to freshwater from the sea, and showing (a) no strontium and (b) high frequencies of strontium. Scales were analyzed from landlocked salmon captured at a head of tide fishway in the Magaguadavic River.

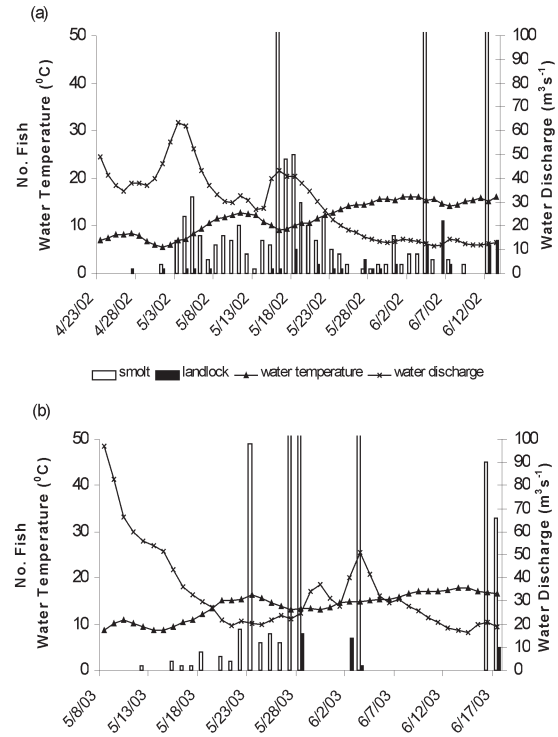

Fig. 3 – The daily numbers of landlocked salmon and anadromous smolt captured in a counting fence trap below the outlet of a downstream fish passage facility in the Magaguadavic River in (a) 2002 and (b) 2003. The water temperatures and discharges are also presented.

Table 1 – Total numbers, origins, fork lengths, tag to body weight ratios, and ages of acoustically tagged landlocked salmon in the Magaguadavic River in 2002 and 2003.

Year	**Origin**	**No. Fish**	**Fork length (cm)**		**Tag to body weight ratio**		**River age**
			Mean±s.d.	Range	Mean±s.d.	Range	Mean (range)
2002	Wild	3	44.2±11.7	36.7-57.7	4.6±2.8	1.4-6.5	4.0 (3-5)
	Hatchery	20	40.1±2.6	37.3-41.8	4.8±0.7	3.9-6.7	3.2 (2-4)
	Total	23	40.7±4.5	36.7-57.7	4.7±1.0	1.4-6.7	3.3 (2-5)
2003	Wild	4	42.0±3.0	39.3-45.5	4.0±0.7	3.1-4.8	3.8 (3-5)
	Hatchery	9	44.7±6.1	39.5-59.6	4.2±1.5	1.1-5.9	4.1 (3-7)
	Total	13	43.8±5.4	39.3-59.6	4.1±1.3	1.1-5.9	4.0 (3-7)

Table 2 – Total numbers, fork lengths, tag to body weight ratios, and number of days to reach river's mouth of tagged fish in the three tracking zones. The biological data is also presented for tagged fish that were lost (signified as 'dead') shortly after initial release. The tracking zones are as follows: Zone 1: seawater section of the Magaguadavic River; Zone 2: Passamaquoddy Bay; Zone 3: Bay of Fundy. No tracking arrays were in Zone 3 during 2003.

Year	Zone	No. Fish	Fork length (cm)	Tag to body weight ratio (%)		No. days to river mouth	
			Mean±s.d.	Mean±s.d.	Range	Mean±s.d.	Range
2002	1	3	39.7±1.2	4.7±0.3	4.5-5.1	4.7±0.3	1-5
	2	9	38.3±0.9	5.1±0.7	4.5-6.5	5.1±0.7	2-22
	3	5	40.9±2.9	4.9±1.2	3.9-6.7	4.9±1.2	2-21
	Dead	6	44.4±7.4	4.0±1.3	1.4-5.1		
2003	1	1	41.5	5.9	5.9	5.9	1
	2	9	44.9±6.2	3.8±1.3	1.1-5.6	3.8±1.3	1-4
	Dead	3	41.6±3.4	4.4±0.6	3.7–4.8		
Combined	1	4	40.2±1.3	5.0±0.6	4.5-5.9		
	2	18	41.6±5.4	4.5±1.2	1.1–6.5		
	3	5	40.9±2.9	4.9±1.2	3.9–6.7		
	Dead	9	43.5±6.2	4.1±1.1	1.4-5.1		

Discussion

The detection of strontium in landlocked salmon scales showed that these fish were indeed moving into the ocean. We had hoped that by analyzing Sr/Ca ratios for individual circuli, we might be able to arrive at a rough estimate from growth rates of the duration the fish spent at sea. Unfortunately, the elemental composition of scales appears to be somewhat unstable, at least for strontium (Courtemanche, 2003), which makes this analysis unworkable.

This study has shown that landlocked salmon can move to and survive in a marine environment for extended periods of time. Migration patterns were highly variable among the tagged fish. Some fish remained in the Magaguadavic estuary, others moved into Passamaquoddy Bay and Bay of Fundy, and some returned to freshwater after up to 55 days at sea. We do not know if these fish underwent a smoltification process similar to that observed for anadromous salmon juveniles moving to sea (Ruggles, 1980).

The out-migrant landlocked salmon seem to be exhibiting a movement pattern typical of many salmonids, however, their migration was not significantly influenced by temperature or water discharge. Anadromous salmon smolt runs typically peak at a water temperature of 10 °C or higher, and the migration period generally lasts for about 30 days (Elson, 1962; Jessop, 1975; Solomon, 1978; Ruggles, 1980; Moore *et al*., 1998). Montgomery *et al*. (1983) reported that the onset of the downstream runs for anadromous brook trout and

Atlantic salmon smolt coincided with declining water levels and discharge.

Landlocked salmon individuals exhibited very different movement patterns, all typical of salmonids but some atypical of the species. The course tracks suggested a tendency for some tagged landlocked salmon to behave similar to sea run charr and trout. Brook trout, Arctic charr (*Salvelinus alpinus*), brown trout (*Salmo trutta*), and cutthroat trout (*Oncorhynchus clarki*) can move from freshwater in the spring of the year to marine environments (near their home river), and return to freshwater in the autumn or winter to spawn or overwinter (Dutil and Power, 1980; McCart, 1980; Castonguay *et al*., 1982; Jonsson, 1985; Trotter, 1989; Finstad and Heggberget, 1993; Gulseth, 2000; Curry *et al*., 2002).

Arctic charr have been documented to spend as few as 10 days at sea, whereas cutthroat trout have spent more than a year in the ocean (Trotter, 1989; Begout Anras and Gyselman, 1999).

Four tagged landlocked salmon moved into the open ocean and were last detected near Grand Manan Island. Anadromous Atlantic salmon postsmolts have been detected in the vicinity of Grand Manan Island on their way to ocean feeding grounds which can be as far away as Greenland (Lacroix, 1996). It is conceivable that this group of landlocks were heading to the species feeding grounds in the North Atlantic.

It is possible that the signals lost (or detected in the same position) in each of the years may have resulted from predation. Of the lost signals, 83% and 67% were from hatchery-reared fish in 2002 and 2003, respectively. Those fish were released during peaks in the anadromous smolt run, a run composed mostly of hatchery escapes from commercial salmon industries along the river. Avian and seal predators were frequently observed during that period just below head of tide.

The higher water discharge experienced in 2003 may explain the increased rate of tagged fish movements to the river's mouth. Aarestrup *et al.* (2002) reported that increased discharges might reduce predation on trout smolts. They suggested that a higher discharge results in higher turbidity, reducing visibility for predators. When smolts move faster, they also reduce their exposure time to riverine predation.

The results from this study suggest that the size of tags did not negatively influence fish survival, movements, and growth. Some studies have recommended that the tag to body weight ratios should not exceed 2% (Fried *et al.,* 1976; Paukert *et al*., 2001). However, Brown *et al*. (1999) reported that Atlantic salmon smolt swimming performance was not affected by tag to body weight ratios ranging from 6 to 12%. In our study, the tag to body weight ratios ranged from 1.1 to 6.7%. The tag to body weight ratios were lower for lost signals (dead fish) than for those fish that remained active for extended periods. We also found that the tagging incision on the two recaptured fish in 2002 had healed and mesentery tissue had begun to surround the tag in the body captivity, less than two months after initial tag implants. Each of the recaptures also had increased in length by about 4% (i.e. had actively fed) since their initial surgery.

The sea lice damage reported on the two recaptured landlocked salmon suggests that levels of infestations could pose a mortality risk to outmigrant salmon smolts, which could contribute to wild salmon declines in the region. Ten of 23-tagged landlocked salmon tracked into Passamaquoddy Bay during this study were detected near sea cages. Carr and Whoriskey (2004) reported sea lice infestations on 21 and 23% of wild anadromous adults and landlocked salmon, respectively, captured over an 11-year period ascending the head of tide fishway trap on the Magaguadavic River. Sea lice infestations have been a major cause of fish mortality and economic loss in the Bay of Fundy salmon aquaculture industry (MacKinnon, 1997).

These results may have major management implications. Some landlocked Atlantic salmon utilize the marine environment. The poor return rates (2 of 38 fish) suggest that there may be a high at sea mortality rate. Given that landlocked fish do maintain the capacity to adapt to seawater, and to undertake ocean movements, it may be possible for rivers that have endangered wild anadromous runs, to utilize landlocked salmon in the system as part of the broodstock in live gene banks for restoring sea-run populations. However, more research is needed to address whether any genetic similarities may exist between anadromous and landlocked populations, especially on a river-by-river basis.

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