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ECOLOGY OF FRESHWATER FISH

Assigning origins in a potentially mixed-stock recreational sea trout (*Salmo trutta*) fishery

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Abstract – The anadromous, or sea-going, life history form of brown trout, or sea trout (*Salmo trutta*), may lead to potential mixing of populations while foraging at sea. In this article, we assess the potential that multiple populations are using common semi-enclosed estuaries and quantify the potential levels of straying (i.e. dispersal) of foreign-produced individuals into populations by using otolith chemical signatures as natural 'tags'. To do so, we created a database of juvenile fish otolith chemistry (a marker of freshwater production) from four rivers and compared the chemistry of harvested fish in two estuaries important to anglers, the Renews River and Chance Cove Brook, to the database. A discriminant function analysis revealed significant differences in the otolith chemistry of juvenile fish inhabiting the four rivers with a 97% cross-validated accuracy when classifying individual juveniles to their natal river, indicating our baseline was robust. When assigning adults caught over 3 years (2007–2009) in the recreational fishery in the Renews River estuary, it was determined that over 95% of the fish caught each year originated from Renews River. In contrast, harvested fish in Chance Cove during 2009 were disproportionately comprised of fish produced in Renews River, suggesting the potential for source-sink population dynamics in Newfoundland. Taken as a whole, these results indicate limited population mixing in nearshore estuaries of this region, but also highlight the potential for some populations to subsidise the harvest by anglers in different areas.

Key words: brown trout; otoliths; origins; LA-ICP-MS

Introduction

Salmon and trout (genera *Oncorhynchus*, *Salmo* and *Salvelinus*) are renowned for distant anadromous migrations, followed by precise homing and spawning in natal locations (reviewed by Klemetsen et al. 2003; Quinn 2005; Jonsson & Jonsson 2011). The duration of time spent at sea and the distance travelled from a home river all fall along a behavioural continuum (Quinn & Myers 2004). Marked variation notwithstanding, an ultimate consequence of anadromous migrations coupled with homing to natal sites is population mixing on the foraging grounds at sea and reproductive isolation among populations on the spawning grounds in freshwater (Hendry & Stearns 2004). As a result, multiple populations may be harvested at the same time and place when fisheries occur during the ocean phase of the life history. Unfortunately, a lack of understanding of population structure in mixed-stock fisheries can lead to inappropriate harvest rates that, when high enough, can drive small or unproductive populations to extinction (Hilborn & Walters 1992). Thus, knowing the extent to which populations mix while at sea is an important step towards implementing sound management.

An increasingly common approach to identify sources of individuals in mixed-stock fisheries is to compare otolith chemical signatures (Campana et al. 2000; Elsdon et al. 2008). The otoliths, or ear stones, of teleost fish are composed primarily of calcium

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carbonate held together by an organic matrix (Campana 1999). Secondary elements such as Strontium (Sr), Magnesium (Mg) and Barium (Ba) can be incorporated into the otolith and are reflective of environmental conditions experienced during rearing, which can then be used as natural tags for stock identification. However, the use of these natural tags requires that each stock or population displays unique chemical otolith signatures (Elsdon et al. 2008). This requirement can be tested either by analysing the water chemistry in which each stock rears, or by examining the otolith chemistry of juvenile fish with known rearing histories. If differences are found among locations, then the juvenile chemical fingerprint can be used as a baseline to facilitate classification of individuals with unknown rearing origins. Importantly, the technique can separate groups of fish that have lived in different habitats but do not vary genetically and therefore can be used on very fine spatial and temporal scales. Encouragingly, a number of studies have successfully employed the use of differential otolith chemistries to associate individuals with habitat (Veinott & Porter 2005; Lara et al. 2008; Patterson & Swearer 2008; Walther et al. 2008; Clarke et al. 2010; Cuveliers et al. 2010) and to quantify recruitment patterns in freshwater recreational fisheries (e.g. Olley et al. 2011; Ramsay et al. 2011).

Here, we use otolith chemistry to assess the extent that populations of brown trout (*Salmo trutta*) overlap while in nearshore marine estuaries; a necessary step towards potential dispersal (i.e. straying) among populations. Brown trout exhibit anadromous (i.e. sea-going) as well as nonanadromous (i.e. freshwater resident) life histories, with the frequency of the migratory life history varying among populations and among individuals within populations (Jonsson & Jonsson 1993). In many regions, the marine migrations by brown trout are short in distance (usually no more than 100 km from the natal river) and limited in duration (individuals often only spend a summer at sea) before fish return to freshwater for spawning and overwintering (e.g. Berg & Berg 1987, 1989; Olsen et al. 2006). On the Avalon Peninsula on the east coast of the island of Newfoundland (Fig. 1), Canada, the anadromous life history form of brown trout, referred to locally as 'sea trout', is a popular sport fish and is frequently targeted in estuaries and coastal waters by anglers (Hustins 2007). Given its importance as a recreational game fish coupled with the potential that non-native brown trout, introduced from Europe in the 1880s, are competing with native salmonids such as Atlantic salmon (*S. salar*) and brook charr (*Salvelinus fontinalis*), it is surprising that so little biological work has focused on brown trout in Newfoundland (Gibson & Cunjak 1986; Westley et al. 2011). In the Northern Hemisphere, it is uncommon for introduced populations of brown trout to exhibit anadromous life histories, despite populations often having access to the ocean. Curiously, it appears that anadromy in brown trout is more common in the Southern Hemisphere (McDowall 2006), which may reflect closer proximity to the ocean by many populations or greater feeding opportunities in higher southern latitudes (Hendry et al. 2004a). Whatever the reasons, the anadromous life history form of brown trout in Newfoundland, and recently detected in Honda et al. (2012), are apparently rare exceptions to the general life history patterns and are not well known. As an applied issue, it is currently unclear whether, and to what extent, populations of anadromous brown trout mix while in the marine environment and therefore are susceptible to angler harvest. In addition, the extent of natal fidelity and distance of marine migrations are not known in Newfoundland brown trout. This lack of biological understanding limits both the ability to implement sound management and the ability to predict the potential of non-native brown trout to further spread.

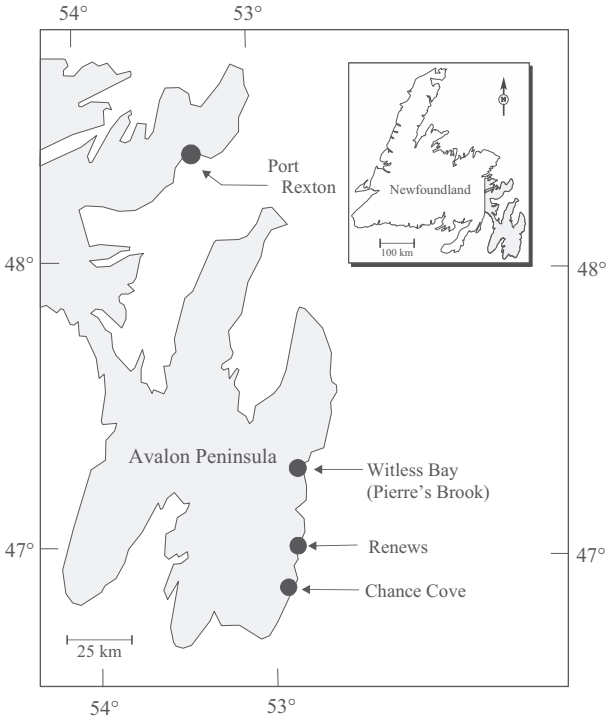

Fig. 1. Map showing sampling locations on the east coast of Newfoundland. Shaded area in the insert is expanded in main map.

In this article, we attempt to address these knowledge gaps by evaluating the stock structure of sea trout captured in a recreational fishery in eastern Newfoundland. The ultimate goal was to determine whether fish caught in a specific semi-enclosed estuary were produced (i.e. spawned and reared while

juveniles) in the river closest to the point of capture. Our objectives were to: (i) create and quantify the utility of a baseline of otolith chemistry from juveniles reared in four rivers, (ii) assign adult fish captured in a potentially mixed-stock fishery to rivers of natal origin using the baseline and (iii) quantify the proportion of locally produced versus foreign individuals captured in the estuaries of two rivers important to anglers. We hypothesised that the proportion of foreign fish captured in estuaries may be high as sea trout in other areas extensively use estuaries and near-shore habitats during marine migrations, thereby increasing the chance of population mixing (Harris & Milner 2006), and because straying into non-natal areas may be atypically common during the early stages of invasion (Hendry et al. 2004b).

Methods

Site description and fish sampling

This study focuses on four rivers popular with anglers targeting anadromous brown trout in eastern Newfoundland, Canada, and specifically on assigning trout captured in the estuaries of the Renews River and Chance Cove Brook to natal locations (Fig. 1). Although information is limited, there is a known migration of sea trout out of the Renews River and into the estuary (a shallow semi-enclosed body of brackish water) and adjacent coastal waters (Veinott 2010). A number of other nearby rivers also support sea trout populations. For a review of the history and current status of the brown trout, invasion readers should see Westley & Fleming (2011).

Juvenile brown trout were collected in 2008 from four rivers (Renews River, Pierre's Brook, Chance Cove Brook and Port Rexton River) on the east coast of Newfoundland (Fig. 1). All juvenile fish were collected using a backpack electrofisher. Pierre's Brook, Chance Cove Brook and Port Rexton were sampled upstream of the tidal influence but within 1 km of the mouth of the river. Every 5th captured brown trout was euthanised with an overdose of clove oil (0.25 mg l^{-1}), and from all of the euthanised fish, a random sample from each river was selected for otolith analyses. Renews River has two natural potential barriers to fish migration; aptly named First Falls and Second Falls, respectively (Fig. 2). First Falls is at approximately river km 1, and Second Falls is at approximately river km 4. In 2008, sampling in Renews River took place upstream of the tidal influence but downstream of First Falls, but yielded few fish ($N = 6$). Thus, we returned in 2009 and expanded our effort throughout the watershed to increase our sample size and to gauge variation in otolith chemistry among individuals reared in different habitats within the Renews River watershed. We collected juvenile trout in locations we designated as 'downstream' (tidal influence to First Falls), 'midstream' (First to Second Falls) and 'upstream' (above Second Falls), respectively and subsequently used in analyses to produce our otolith chemistry baseline.

Harvested fish were provided by anglers from the recreational fishery in the Renews estuary. Occasionally whole fish were provided but most often only the heads, or heads and entrails were collected. Samples were placed on ice and transported to the laboratory where they were frozen at −20 °C. The modal

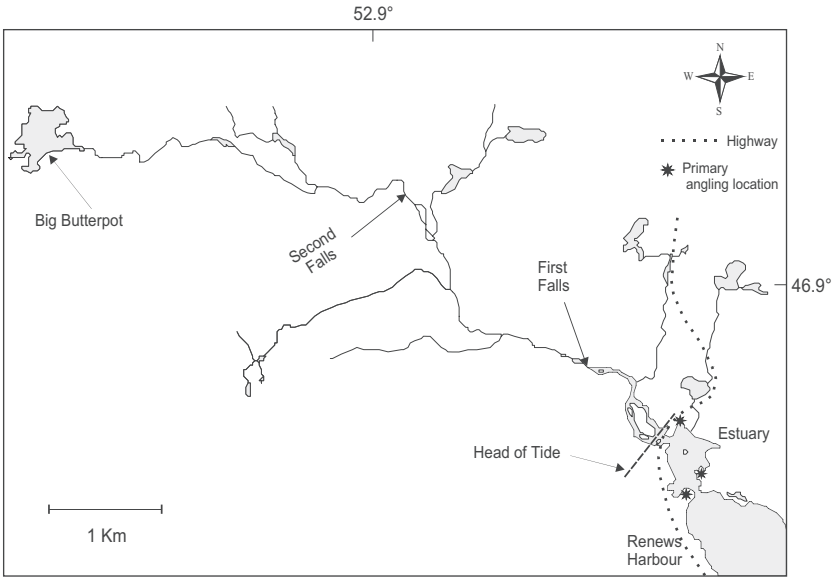

Fig. 2. Map of the Renews River watershed showing locations used to delineate sampling areas.

age of fish migrating out of Renews River was 3+ (Veinott 2010) which is the same as for fish harvested in the recreational fishery, but evidence of spawning marks on the scales did not occur until age 4+ (Veinott 2011). Despite the discrepancy, we refer to fish harvested in the recreational fishery as 'adults' for clarity. In 2007, the recreational fishery was sampled opportunistically, whereas in 2008 and 2009, a standardised creel survey (Malvestuto et al. 1978; Beckley et al. 2008; Veinott 2011) was conducted. In each year, a subsample, selected to represent the observed size distribution of harvested fish across seasons, was selected for otolith chemical analysis. By 2009, anglers in the area were aware of this study and volunteered harvested fish from other locations including the Chance Cove estuary. All of the Chance Cove samples were analysed for otolith chemistry. The ultimate decision on sample sizes used in the analyses reflects a trade-off between specimen availability and funding to run the samples, but is in line with other studies (e.g. Patterson & Swearer 2008; Gibson-Reinemer et al. 2009; Zitek et al. 2010).

Otolith sampling and analyses

Otoliths were removed from the fish, cleaned in deionised water, air dried and placed in individual plastic vials for storage. To expose the early life growth in the adult fish, otoliths were embedded in epoxy and sectioned following Jenke (2002). Otoliths of both angled adults and electro fished juveniles were then mounted on glass slides using two-sided tape; only the adult otoliths were sectioned, whereas juveniles were mounted whole with the sulcus side down.

To determine trace element composition, otoliths were ablated using a Geolas 193 nm ArF excimer laser system attached to a Thermo Element-XR double focusing sector field ICP-MS. The laser was fired at a rate of 10 Hz and had an output energy of approximately 0.15 mJ (12 $J \cdot cm^{-2}$). On sectioned otoliths the laser travelled across the surface of the otolith from the primordium (i.e. core or centre) to the growing edge along the axis of maximum growth at a rate of 10 μm s^{-1}. For whole otoliths (juveniles), the laser was held stationary and a hole was drilled into the centre of the otolith (Veinott et al., unpublished). Ablated material was carried to the ICP-MS by a 1.1 $l \cdot min^{-1}$ flow of He, where it combined with a stream of Ar carrier gas at 0.70 $l \cdot min^{-1}$ before reaching the ICP as a dry aerosol. All measurements at the ICP-MS were performed in time resolved analyses mode utilising peak jumping mode with 1 point per mass peak. Integration time was 10 ms per mass, with a settling time of 1 ms per mass. A typical acquisition consisted of a 20- to 30-s measurement of the gas blank before the laser was switched on (background), followed by 100- to 200-s measurement with the laser on and material being ablated depending on whether the laser was drilling or scanning.

Raw counts of Calcium (Ca^{43}), Magnesium (Mg^{24}), Manganese (Mn^{55}), Zinc (Zn^{66}), Strontium (Sr^{88}) and Barium (Ba^{137}) from the ICP-MS were processed off line using LAMTRACE software produced by Memorial University (Longerich et al. 1996). Calcium ratios were calculated to compensate for changes in ablation efficiency between scans or along a single laser scan. However, normalising laser ablation data to Ca does not correct for mass-dependent changes in instrument sensitivity that can occur throughout the day (drift) or after the instrument has been shut off and re-tuned after start-up. Therefore, to compare laser data over longer periods of time, the element:Ca ratios must be compared to a standard reference material. Therefore, the National Institute of Standards and Testing, standard reference material 612 (trace element spiked glass bead), was used to convert background corrected data to concentrations (parts per million).

Rather than treat each 10-ms cycle of the ICP as an independent sample, approximately 1 s of background corrected data was averaged and then used to produce a concentration for each element in that 1 s of ablated material. Statically, this is equivalent to ablating the material for a short time, taking the average counts for that time then continuing to ablate new material. Running a continuous scan or drilling (as we did with the juvenile otoliths) and dividing the counts into discrete 1-s blocks simply facilitate the analyses.

Sampling and analysing freshwater growth in otoliths

To assign marine caught fish to a particular river requires that the otolith material that is analysed and compared be produced during a period of river residency. For juvenile fish, it was assumed that no marine migrations had occurred as fish were sampled at an age and size prior to seaward migrations. Therefore, all materials deposited on the juvenile otolith after emergence should reflect the water chemistry in the river of natal origin. Test drilling in the centre of a sample of otoliths found that no transgenerational Sr marks (Kalish 1990) occurred within 20–30 μm of the surface of the otoliths. Therefore, in juvenile otoliths, the first 5-s of drilling was discarded to eliminate surface contamination, and the second 5-s of drilling was used in the analysis. This is equivalent to approximately 5 μm of otolith material.

All the harvested adults used in the study were captured in estuarine waters and as expected, each otolith revealed a distinct rise in Sr concentration indicating the transition from fresh to saline waters

(Fig. 3). The beginning of this transition was used to indicate the end of the freshwater growth phase, and therefore, material ablated just prior to the entrance to marine waters was used in the analyses to determine river of origin. Ten seconds of ablation which is approximately 100 μm of otolith material was averaged to provide elemental concentrations for that portion of the freshwater growth (see Fig. 3).

Baseline construction with juvenile otoliths and assignment of adults

We used discriminant function analysis (DFA) in the SAS Enterprise Guide 4.2 statistical software package (SAS Institute Inc., Cary, NC, USA) to differentiate among chemistry of juvenile otoliths from freshwater and to create a baseline for comparison among estuary harvested adults. All elemental concentrations were log transformed prior to the DFA. The first attempt to identify group membership based on otolith chemistry was carried out on the within-river samples from Renews River. The classification variable was the within-river location (downstream, midstream or upstream), and the dependent variables were the Mg, Mn, Zn, Sr and Ba concentrations. Prior probabilities were based on sample size, and a jackknifed classification was computed. This within-river analysis was carried out to first determine whether adults could be assigned to specific locations within the river, or conversely, whether juveniles from Renews River could be pooled. However, after cross-validation, the DFA only correctly assigned 14 –50% of the juveniles to their collection location within the Renews River (Table 1). We interpreted these results as insufficient to confidently assign adults to specific within-river locations nor poor enough to pool the sample. Therefore, we constructed the Renews River baseline using the 2008 samples and the 2009 juveniles collected in the downstream location only. In addition to the results of the DFA above, we consider this additionally justified to be consistent with sampling protocols in the other rivers (fish from downstream areas used), and because brown trout disproportionately use the downstream areas of the Renews River watershed for rearing (Warner et al. unpublished data). One of the 2008 juvenile samples was dropped prior to the analyses because of its unusually high Sr concentration (>1800 ppm) that was more consistent with estuarine growth rather than freshwater growth and may have been a fish that had previously resided in the estuarine environment.

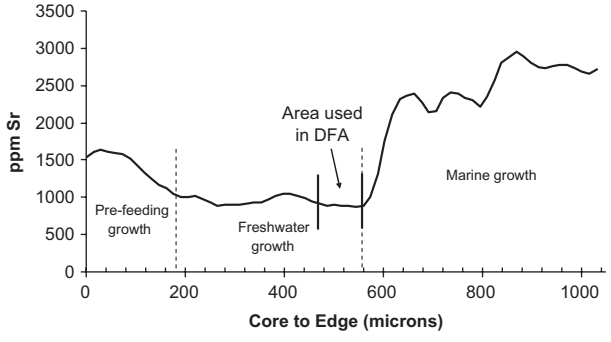

Fig. 3. Relationship between strontium (Sr) concentrations in the otolith and distance from the otolith core in an estuary angled fish. Dashed vertical lines delineate areas of prefeeding, freshwater and marine growth. Solid vertical lines delineate area of the otolith used in the discriminant function analysis (DFA).

Table 1. Number (per cent) of juvenile fish from within Renews River classified by the DFA into the different sampling sites.

	Into Site			
From Site	DS	MS	US	Total
DS	8 (50)	6 (37.5)	2 (12.5)	16 (100)
MS	8 (67)	2 (17)	2 (17)	12 (100)
US	5 (71)	1 (14)	1 (14)	7 (100)
Total	21 (60)	9 (26)	5 (14)	35 (100)

DFA, discriminant function analysis; DS, downstream; MS, mid stream; US, upstream.

The analytical approach to construct discriminant functions to assign adult fish to natal origins was the same as described previously, except classifications were based on the juvenile baseline. That is, once the initial jackknifed classification of juveniles was completed that juvenile 'training data' were used to classify a new data set that consisted of the otolith elemental concentrations from the adult trout captured in the recreational fishery. Each year (2007, 2008 and 2009) for which samples from the recreational fishery were available was analysed separately.

Results

Juvenile samples from freshwater

Mean juvenile otolith elemental concentrations varied among rivers but were relatively stable among sites within Renews River and between the Renews River 2008 and 2009 samples (Fig. 4). The otoliths of juveniles from Chance Cove and Port Rexton had the highest Mg and Zn concentrations, and Port Rexton had the lowest Sr concentration. Pierre's Brook samples had the highest Mn and Sr concentrations, whereas Renews River fish had the highest Ba concentrations in their otoliths. The greatest variation between years was in the Mg and Zn concentrations.

On the basis of the freshwater juvenile otolith chemistry, the among-river DFA was able to clearly separate individuals based on their natal rivers (Fig. 5a). The first discriminant function was able to

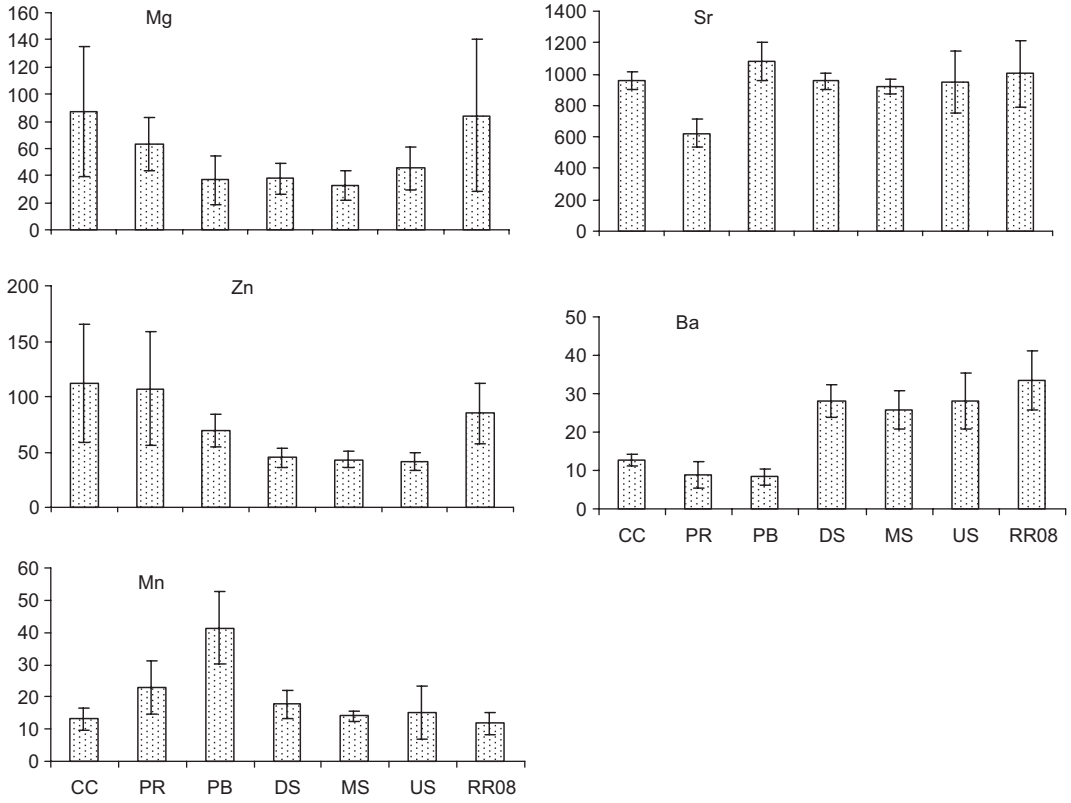

Fig. 4. Mean freshwater concentrations (ppm) of Mg, Zn, Mn, Sr and Ba in juvenile brown trout used in the construction of the baseline for the discriminant function analysis (DFA). CC, Chance Cove; PR, Port Rexton; PB, Pierre's Brook; DS, Renews River down stream; MS, Renews River mid stream; US, Renews River upstream; RR08, Renews River 2008 samples. Error bars represent 95% confidence intervals.

separate Renews River samples from Chance Cove and Pierre's Brook samples, and the second discriminant function separated Renews River from Port Rexton. With the use of a jackknifed classification procedure, there was only one misclassification – a Port Rexton fish classified as a Chance Cove individual (Table 2).

Angler samples from estuary fisheries

From the 2007 recreational fishery in the Renews estuary, 42 of the 45 fish analysed (95.5%) were classified as Renews River individuals (Table 3). Of the three fish not assigned to the Renews River group, one fish was assigned to each of the other three rivers (Fig. 5b). From visual inspection of Fig. 5b, the one fish classified as a Pierre's Brook individual (Fig. 5b Arrow top right) is immediately apparent. Given the clear separation of Pierre's Brook fish from Renews fish, it is likely this is a true migrant from Pierre's Brook. The other two fish not assigned to Renews River fall along an imaginary line from the bottom left to the top right of Fig. 4b that seems to be a border between Renews fish and the other three rivers. It is difficult to robustly state that these fish are true migrants from those other rivers given the variation of the adult data around the Renews River training data (i.e. juveniles) cluster. The amount of variation around the Renews training data is likely a function of the within-river variability, observed in the within stream DFA (Table 1), and that the angled fish are of different ages. The different age classes would have migrated from the river in different years which presumably also resulted in some variation in their freshwater otolith chemistry signatures. Similar variation, as was seen in 2007, was observed around the DFA training data when the otoliths analysed from the 2008 recreational catch from the Renews estuary were plotted (Fig. 5c). However, in 2008, 100% of the fish (N = 25) were classified as of Renews River origin.

The 2009 sample of the recreational fishery included individuals harvested in the Renews estuary (N = 53) and the Chance Cove estuary (N = 9). For the fish harvested in the Renews estuary, 96% were classified as of Renews River origin. The two fish harvested in Renews but not classified as of Renews River origin (Fig. 5d arrows) were assigned to Chance Cove River. In contrast, of the nine fish harvested in the Chance Cove estuary, only two (22%) were classified as Chance Cove River fish. The remaining seven fish harvested from Chance Cove

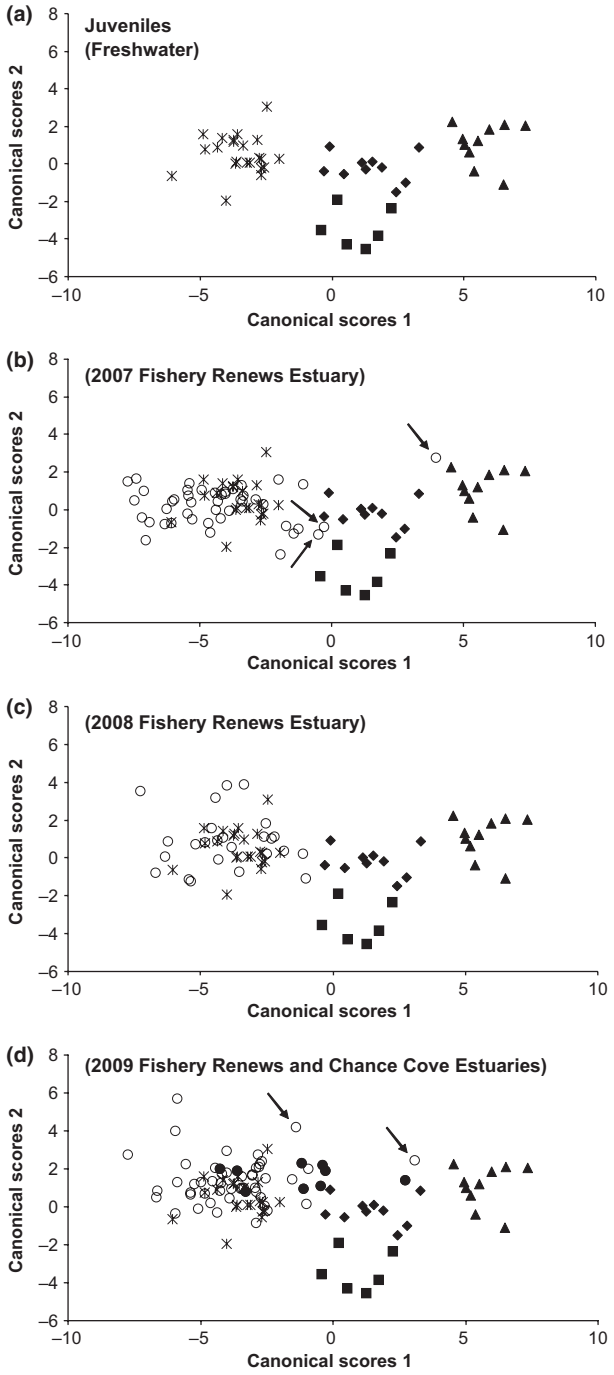

Fig. 5. Plots of the first and second canonical scores from the discriminant function analyses. Triangles, Pierre's Brook; Diamonds, Chance Cove; Squares, Port Rexton; Stars, Renews River; Open Circles, Fish angled in Renews estuary; Closed Circles, Fish angled in Chance Cove estuary. Panel a is from the in-river juveniles, added are the angling data from 2007 (b), 2008 (c) and 2009 (d). Arrows indicate fish angled at Renews but not assigned to Renews River.

were classified as Renews River fish. However, based on Fig. 5d, the Chance Cove fish are widely distributed along the first canonical axis. For example, there is a single individual with a first canonical score of approximately 2.5. Then, there is a cluster of five Chance Cove fish near the origin which is on the border between Renews fish and all other rivers. Finally, in Fig. 5d, there is a cluster of three Chance Cove fish directly on top of the Renews River juvenile cluster. The close proximity of the Chance Cove fish to the Renews training data means that the otolith chemistry of all of these fish is nearly identical suggesting that these fish truly originated from the Renews River.

Table 2. Number (per cent) of juvenile fish from each river classified by the DFA into local versus foreign rivers.

	Into Site				
From Site	CC	RR	PR	PB	Total
CC	10 (100)	0 (0)	0 (0)	0 (0)	10 (100)
RR	0 (0)	22 (100)	0 (0)	0 (0)	22 (100)
PR	1 (17)	0 (0)	5 (83)	0 (0)	6 (100)
PB	0 (0)	0 (0)	0 (0)	10 (100)	10 (100)
Total	11 (23)	22 (46)	5 (11)	10 (21)	48 (100)

DFA, discriminant function analysis; CC, Chance Cove; RR, Renews River; PR, Port Rexton; PB, Pierre's Brook.

Discussion

In this article, we examined the population structure in a potentially mixed-stock recreational fishery for sea trout and the results yielded several salient points. First, we showed that otolith chemistry in juveniles reflects site-specific conditions and can be used successfully to differentiate among anadromous adults later in life. Second, we found evidence counter to our predictions of high population mixing, but detected variation in the extent of mixing among rivers. For example, of the 118 fish harvested in the Renews River estuary over 3 years, 96% were classified as having been produced in that river, whereas only 22% of fish captured at the Chance Cove estuary were clas-

Table 3. Sample sizes, average (±SD) fork length (cm), modal (range) age inferred from scale annuli and percentage of sea trout harvested in Renews estuary and assigned to the Renews River population based on natural chemical tags in the otoliths during the spring, summer and fall of 2007–2009.

Year	Season	*N*	Length (cm)	Age	*N* (%) Renews River
2007	Spring	1	38	–	1 (100)
	Summer	39	29.1 (5.9)	3 (2–6)	37 (95)
	Fall	5	36.2 (5.4)	4 (3–5)	4 (80)
2008	Spring	10	34.1 (12.1)	4 (3–8)	10 (100)
	Summer	15	28.9 (8.3)	4 (3–6)	15 (100)
	Fall	–	–	–	–
2009	Spring	21	34.6 (11.2)	4 (3–7)	21 (100)
	Summer	17	30.2 (7.2)	4 (3–5)	15 (88)
	Fall	10	25.3 (5.0)	3 (3–5)	10 (100)

sified as locally produced individuals. These patterns suggest the potential for meta-population and source-sink dynamics among recently established brown trout populations in Newfoundland. Taken as whole, the results confirm the role of otolith microchemistry as a useful tool for identifying stock structure in marine recreational fisheries for anadromous species and suggest limited overlap among populations in estuaries, migrations of short distances, and that individuals from some populations may act as harvest subsidies to anglers in other locations. Given these results, we suggest conservation towards the maintenance of the processes that produce these patterns if there is a long-term goal of sustainable angler harvests. However, we acknowledge the unenviable dilemma faced by managers to balance the contradictory calls to treat non-native brown trout as a prize worth preserving, or a pest to eradicate.

The use of otolith chemistry is an increasingly common tool to infer stock structure in recreationally important species (Patterson & Swearer 2008; Wells et al. 2010; Newman et al. 2011; Ramsay et al. 2011). For example, Walther et al. (2008) found that only 6% of spawning American shad (*Alosa sapidissima*) in the York River system in Virginia were produced elsewhere and thus were potential strays from other rivers, and Olley et al. (2011) were able to use otolith chemistry to show that recruitment sources for brown trout were spread evenly throughout their study catchment. However, to the best of our knowledge, our study was the first to investigate population mixing between catchments in sea run brown trout in a recreational fishery. Despite their obvious utility, otolith chemistry is not a panacea immune to caveats and assumptions. In this study, we make several common assumptions that are worthy of discussion. First, we assume that chemistry in the four rivers we sampled is stable through time. We detected greater variability in chemistry of harvested fish compared with juvenile fish, which we interpret as arising from at least two potential, not mutually exclusive, pathways. First, the assumption of temporal stability in water chemistry within rivers may not be entirely justified. Our samples of harvested fish from the Renews River estuary were comprised of multiple age classes and migratory histories. Not only were individuals necessarily compared to chemistry several years *after* they reared in the river, but in addition there was variation of when fish emigrated to sea and thus temporal differences of when they were rearing in freshwater. The variability detected in the harvested adult otolith may reflect temporal differences in chemistry, suggesting instability in environmental signatures. However, the temporal chemistry variability is not sufficient to result in the assignment of individuals to rivers other than Renews.

Second, the influence of 'ghost' populations (i.e. populations we did not sample but that may have chemistry similar to Renews) may be reflected in the greater variability in adult versus juvenile chemistry. The east coast of the Avalon Peninsula has at least eight watersheds with established populations of brown trout (Westley & Fleming 2011), though we were only able to sample three. We chose these locations as they are important areas for recreational fishing and because they are relatively large watersheds (88, 102 and 76 km^2 for Chance Cove, Pierre's Brook, and Renews, respectively compared to mean size of other watersheds 78 km^2, range 51 –123 km^2). The large area likely translates to greater habitat for the production of potential strays and migrants compared to smaller watersheds. Our analyses allow us to confidently say that few migrants from Chance Cove or Pierre's Brook are inter-mixing with Renews fish in the estuary, and only one potential migrant from Port Rexton a watershed at the edge of the brown trout range in Newfoundland, 271 km as a fish swims from Renews, was detected. Whether individuals from unsampled watersheds are represented in the sample of adults harvested in the Renews River estuary is not known, but seems unlikely.

Assumptions and caveats notwithstanding, our results reveal that, on average, 96% of the fish caught in the Renews recreational fishery were of Renews River origin, suggesting short-distance marine migrations. Our data are consistent with the general consensus that while at sea, trout typically remain close to their home river, but individual and site-specific variation is considerable (Klemetsen et al. 2003). For example, of 2122 sea trout tagged leaving the river Vardness, Norway, 52.8% were caught within 3 km of the river mouth, and only 0.6% travelled more than 80 km distance (Berg & Berg 1987). In contrast, sea trout from the northwest Iberian Peninsula, Spain, typically travelled in excess of 200 km from their tagging site in the Ulla River (Caballero et al. 2006), and populations in the Black Sea may migrate as far as 900 km from the point of release (Okumus et al. 2006 and references therein). Thus, while sea trout have the capacity to migrate long distances, typically they do not. Our data support the consensus of limited marine migrations in Newfoundland sea trout. The most likely source of foreign fish in the Renews fishery is Chance Cove, followed by Pierre's Brook. Chance Cove contributed 2.5% of the harvest from the Renews fishery, whereas Pierre's Brook contributed <1%. These patterns likely, at least in part, reflect distance between watersheds (Chance Cove and Pierre's Brook are 24 and 61 km from the Renew River, respectively), and migratory costs incurred by sea trout. That is, trout may not migrate

far from home and if they do go elsewhere are more likely to enter a nearby, rather than distant, estuary.

Anadromy and homing are behaviourally coupled in sea trout and other salmonids (McDowall 2001), and both are thought to reflect and promote local adaptation to environmental conditions (Quinn 2005). The small proportion of nonlocal individuals detected in the Renews River estuary suggest limited potential for straying of foreign individuals into the system. Efforts to quantify rates straying in salmonids are exceedingly difficult, due in part, because individuals can stray *into* and *out of* populations (Quinn 1993). In this article, we assess potential straying of foreign individuals *into* the Renews River and consider these data to be indicative of maximum potential straying rates. Individuals may have left the Renews estuary and gone to their home river if given the choice, but they of course were not as they were all killed by anglers. Additionally, straying conventionally implies spawning and gene flow among populations (Quinn 1993), but whether the fish caught in the Renew estuary were there simply for feeding or were indeed headed upriver to spawn is unknown. If fish were in the estuary primarily for feeding, one might have expected foreign individuals to be more common in the Renews estuary during the nonreproductive season (spring and summer). In contrast, we detected consistent local dominance during all seasons (Table 3). Our estimates of a potential 5–7% stray rate are within the range of published estimates (see review by Jonsson & Jonsson 2011), which combine to suggest that brown trout home with marked fidelity. Indeed, fine scale local adaptation observed in brown trout populations also implies accurate homing as excessive gene flow would likely erode adaptation in the absence of philopatry (Hendry et al. 2004b; Meier et al. 2011).

We detected the potential for the Renews River population to contribute disproportionately to the harvest in the Chance Cove fishery (seven of the nine harvested fish in Chance Cove estuary were identified as of Renews River origin), at least at certain times. The high-proportion of foreign fish in Chance Cove includes periods of the fall when adults would be maturing. These patterns highlight the potential for source-sink dynamics among brown trout populations in Newfoundland (Schtickzelle & Quinn 2007); however, a small sample of harvested fish at Chance Cove collected in September and October of the same year necessitates caution in interpretation. Unknown details about the Chance Cove and Renews River populations, such as their relative size, make conclusions difficult. Even a modest straying rate in a numerically large population can result in a high absolute number of strays and may then comprise a large proportion of the total fish returning in a numerically small population. Regardless, the results suggest the potential for population mixing and dispersal, and that harvests within a watershed may be subsidised from other areas. Productivity among populations can change through time (Hilborn et al. 2003; Schindler et al. 2010), and thus, it is prudent to maintain population structure and connectivity of brown trout populations assuming that long-term sustainable harvests are the goal.

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