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BRIEF COMMUNICATION

Anadromy and marine habitat use of Lake trout (*Salvelinus namaycush*) from the central Canadian Arctic

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Abstract

Anadromy was documented in 16 lake trout, *Salvelinus namaycush*, from Canada's central Arctic using capture data and otolith microchemistry. For the first time, estuarine/marine habitat use was described for five individuals using acoustic telemetry. Age-at-first-migration to sea was variable (10–39 years) among individuals and most *S. namaycush* undertook multiple anadromous migrations within their lifetime. Telemetry data suggested that *S. namaycush* do not travel far into marine habitats and prefer surface waters (<2 m). These results further our collective understanding of the marine ecology of Arctic *S. namaycush*.

KEYWORDS

Lake Trout, *Salvelinus namaycush*, Anadromous migrations, marine

Anadromy – directed migration from freshwater habitats used for spawning, rearing and overwintering to marine habitats for foraging – is a common life history strategy for salmonids (Hendry *et al.*, 2004; McDowall, 2008) and allows fish to access productive marine environments at latitudes where freshwater productivity is generally low (Gross *et al.*, 1988). Northern chars (Genus *Salvelinus*) are often partially anadromous, which means that one contingent of the population remains in freshwater whereas the other undertakes annual marine migrations (*e.g.*, Kissinger *et al.*, 2016; Swanson *et al.*, 2010). Partially anadromous populations can vary markedly in the proportion of the population that migrates, age-at-first-migration (AFM) to marine habitats and the lifetime frequency of these migrations (Kissinger *et al.*, 2016; Swanson *et al.*, 2010). Detailing such intrapopulation variation in habitat use and migratory tactics has important implications for management and the conservation of biodiversity (Schindler *et al.*, 2010), and improves our ability to make predictions regarding climate change impacts (Reist *et al.*, 2013).

Until recently, lake trout, *Salvelinus namaycush* (Walbaum 1792), were commonly regarded as the only nonanadromous char species in North America based on field observations (Hendry *et al.*, 2004) and laboratory assessments (Hiroi & McCormick, 2007), despite being documented in marine habitats at high latitudes over 60 years ago (Weed, 1934; reviewed in Martin & Olver, 1980). This presumption was supported by the fact that *S. namaycush* are stenohaline, exhibiting marked disruptions in ion homeostasis when exposed to elevated salinities (Hiroi & McCormick, 2007). *S. namaycush* do, however, possess some capacity to regulate plasma ion levels in saltwater (Hiroi & McCormick, 2007; Kissinger *et al.*, 2017), and it has recently become clear that they can utilize this capacity to support some degree of anadromy (Kissinger *et al.*, 2016; Swanson *et al.*, 2010).

On southern Victoria Island in Canada's Central Arctic, there have been accounts of *S. namaycush* in brackish and marine waters (Coad & Reist 2018) that are characterized by shallow depths and low salinities compared to other marine areas of the Canadian Arctic (Harris *et al.* 2020). It is therefore reasonable to predict that the frequency of

S. namaycush anadromy in this region might be higher than that in other Canadian Arctic regions. Indeed, anadromous populations are known on the mainland of the Canadian Arctic (Swanson *et al.*, 2010), however, the ecology of anadromous *S. namaycush* is still not well characterized and no studies have directly studied habitat use in this species during their marine migrations.

In 2014, a community-based sampling program was initiated in the Cambridge Bay region (Figure 1a) where local Arctic char, *S. alpinus* L., fishers were offered rewards for recording *S. namaycush* captured in marine waters and for collecting otoliths from these fish. Between 2014 and 2016, 14 *S. namaycush* were collected from marine/brackish waters and otolith microchemistry analysis was performed on 10 individuals (Table 1). In this region, we have also maintained an array of VR2W acoustic receivers (Vemco, Halifax, NS, Canada) for studying the migratory ecology of *S. alpinus* since 2013 (Moore *et al.*, 2016,

Figure 1a,b). As part of this work, five *S. namaycush* were opportunistically tagged in the estuary at the mouth of the Ekalluk River (Table 1 and Figure 1). These fish were surgically implanted with V16 acoustic transmitters (Vemco, see Moore *et al.*, 2016 for details), three of which recorded depth and temperature. Our acoustic tagging was approved by the Fisheries and Oceans Canada Animal Care Committee in each year of study and the procedure conforms to all animal care laws in Canada (permit no. FWI-ACC-2013-2019). The receiver placement of our array specifically allowed us to document movements between marine and lake habitats in the Ekalluk River system.

Details of the microchemistry analyses are described in Swanson *et al.* (2010). Briefly, otoliths were transversely sectioned before being analysed using laser ablation-inductively coupled mass spectrometry. Strontium profiles were overlaid on post-ablation photos of otoliths, and outliers that resulted from cracks in otoliths or rough surfaces

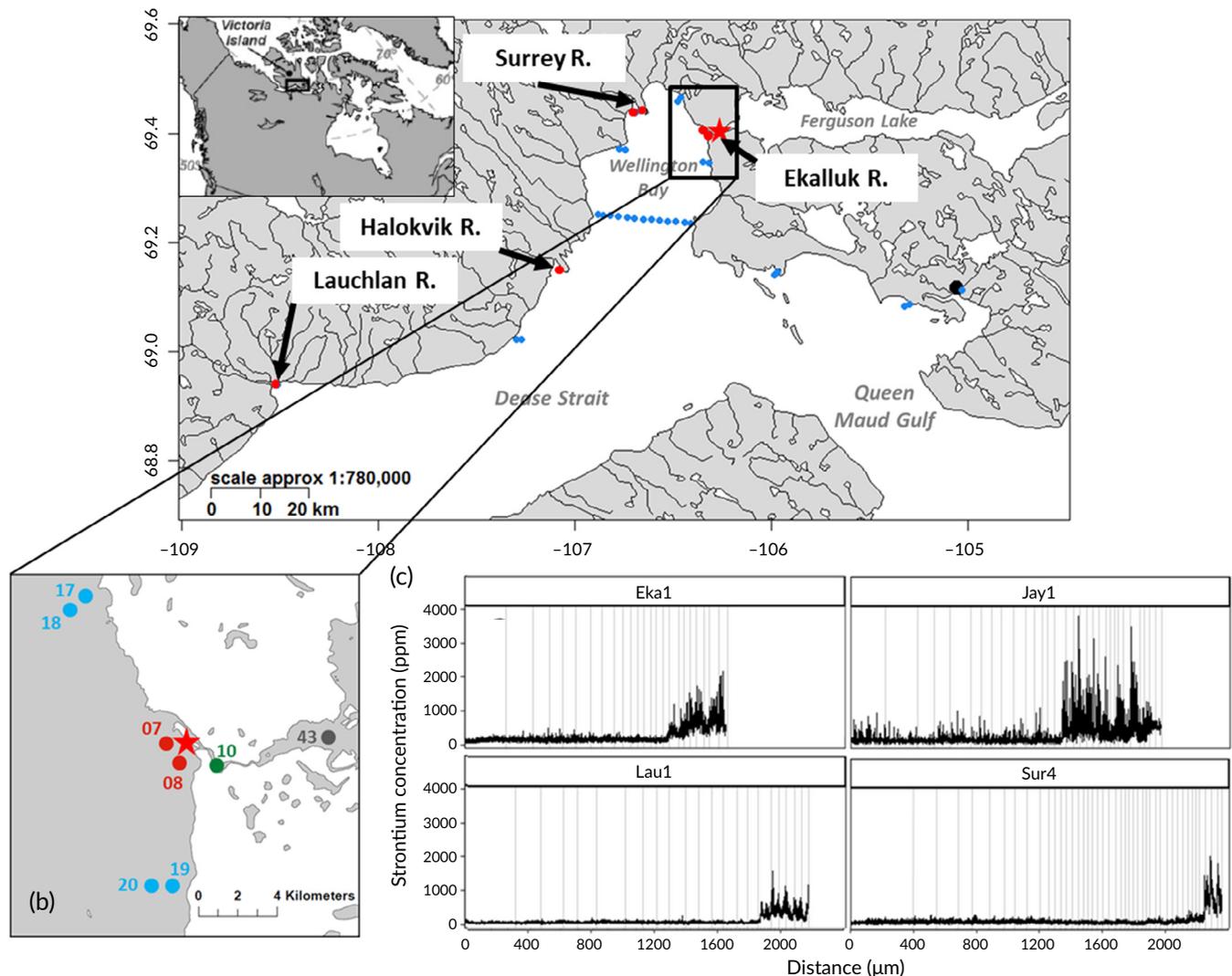


FIGURE 1 (a) Acoustic telemetry array near southern Victoria Island, NU. Red (estuary stations) and blue (marine stations) circles indicate the locations of the individual receivers. The Ekalluk River tagging location is indicated by a red star and the community of Cambridge Bay by a black circle. (b) The immediate study area near the mouth of the Ekalluk River showing lake (grey circle), river (green circle), estuary (red circles) and marine (blue circles) acoustic stations and associated station numbers. (c) Otolith strontium profiles of four anadromous *S. namaycush* from the Cambridge Bay region. Full details for of otolith Sr analyses for each individual are shown in Table 1

TABLE 1 Results from otolith microchemistry (strontium) analyses showing, for each *S. namaycush* analysed, the sample ID, location of capture, age, age-at-first-migration, total number of years an anadromous migration was inferred for each individual and maximum Sr detected for each individual

| Sample ID | Capture location | Age | Age-at-first-migration | Number of years | Maximum Sr |
|-----------|------------------|-------|------------------------|-----------------|--------------|
| Eka1 | Ekalluk | 24 | 16 | 6 | 2158.3 |
| Eka2 | Ekalluk | 31 | 15 | 9 | 1588.3 |
| Eka3 | Ekalluk | 34 | 34 | 1 | 307.9 |
| Jay1 | Jayko | 31 | 15 | 9 | 3815.4 |
| Jay2 | Jayko | 36 | 32 | 3 | 2874.8 |
| Lau1 | Lauhlan | 22 | 16 | 8 | 1602.8 |
| Sur1 | Surrey | 27 | 24 | 2 | 961.1 |
| Sur2 | Surrey | 39 | 39 | 1 | 226.3 |
| Sur3 | Surrey | 45 | 45 | 1 | 416.8 |
| Sur4 | Surrey | 44 | 31 | 4 | 2098.9 |
| | Mean | 33.3 | 26.7 | 4.4 | 1605.1 |
| | Range | 22–45 | 16–45 | 1–9 | 226.3–3815.4 |

were manually removed. A three-point smoothing averaged was used to reduce noise related to background variability in carrier gas flow. Anadromy was inferred from profiles of strontium concentration normalized to calcium and an external standard. Strontium (Sr) concentrations <500 ppm were considered indicative of freshwater habitat use whereas Sr > 500 ppm was considered indicative of brackish/marine water habitat (Harris *et al.*, 2012; Kissinger *et al.*, 2016). *S. namaycush* analysed for otolith microchemistry ranged in age from 22 to 45 years (mean = 33.3; Table 1). Strontium profiles revealed remarkable variability in inferred habitat use and migratory behaviour. Three individuals appeared to have been migrating to marine/brackish waters for the first time when captured in river estuary habitats (Eka3, Sur2 and Sur 3), as they exhibited low (<500 ppm), constant (flat) Sr from the core to the outer edge of the otolith (Figure S1); we posit that this was due to insufficient time for Sr uptake into the otoliths (Eldson & Gillanders, 2005). The other strontium profiles revealed varying degrees of marine habitat use (Figure 1c and Supporting Information Figure S1). AFM was variable among and within the four populations represented (15–45 years, mean = 26.7 ± 11.04S.D.; Table 1). Most individuals had undertaken numerous annual migrations to marine or brackish water habitats (Table 1, Figure 1c and Supporting Information Figure S1) and there were multiple cases of 'skipped' migrations (*i.e.*, marine migrations followed by one or more summers spent in freshwater).

The average AFM and its range were higher in this study than those previously reported by Swanson *et al.* (2010; mean AFM 13 years, range 3–29) or Kissinger *et al.* (2016; range 8–14) for other Canadian Arctic systems. It is not clear why mean AFM was so high in our system, but it could reflect variability in migration length between freshwater and marine environments, differences in early freshwater growth rates and/or differences in freshwater vs. marine productivity between regions (Gross, 1987). Future modelling of growth based on changes in the width of otolith growth increments may help shed light on potential growth-rate thresholds that may influence the timing,

prevalence and frequency of anadromous *S. namaycush* migrations in our system. Indeed, increased growth rates and longevity have been described for other Arctic populations of *S. namaycush* that access marine and brackish waters (Kissinger *et al.*, 2019), highlighting the potential importance and life history of migrating to these habitats.

Maximum Sr (226.3–3815.4) observed were more consistent with brackish water habitat use than with full-strength seawater (Harris *et al.*, 2012; Kissinger *et al.*, 2016). Indeed, marine migrations in this species could be viewed as a form of "semi-anadromy2" (Swanson *et al.*, 2010), defined as a preference for brackish water habitats over full-strength seawater. Here, this likely relates to the preferential use of estuarine habitats that are less saline and warmer than marine habitats (see Harris *et al.*, 2020). This would suggest that *S. namaycush* in the region do not travel far from the mouths of the rivers once they have accessed the estuary, an interpretation supported by our telemetry data.

From 2014–2019, we recorded 77,451 detections, 16,920 of which were considered estuary/marine detections (Table 2 and Supporting Information Figure S2). Ekalluk River *S. namaycush* were only detected at two estuary stations (stations 07 and 08) and one marine station (station 19 located ~9 km from the Ekalluk River estuary, Figure 1b; see Harris *et al.*, (2020) for a description of all marine/estuarine stations and how they were classified). The total number of days spent in estuary/marine habitats per individual ranged from 1 to 71 (mean = 25 ± 28.9S.D.) days across all years. Three *S. namaycush* were only detected in the marine environment in 1 year, one individual over 2 years and one individual migrated to the Ekalluk River estuary in five consecutive years (Table 2 and Supporting Information Figure S2). Of the 16,920 detections, all but 116 were at estuary stations 07 and 08 (Figure 1). The 116 marine detections involved two fish (IDs 27805 and 24668) that were briefly detected at station 19 (Figure 1b). Mean depth use by individual *S. namaycush* ranged from 0.55 to 1.55 m, indicating a preference for surface waters, although dives below 10 m were also recorded in two

TABLE 2 Summary of acoustic telemetry data for *S. namaycush* tagged at the Ekalluk River estuary, including the acoustic tag ID, tag date, length and weight, total number of acoustic detections and those that were considered marine or estuary (Mar/Est), total number of days detected in marine or estuarine habitats and number of years detected in marine or estuarine habits, including the specific years in which each individual was detected

| Tag ID | Date tagged | Fork length (mm) | Round weight (g) | Total detections | Detections in Mar/Est | Number of days in Mar/Est | Number of years in Mar/Est | Years detected |
|----------|-------------|------------------|------------------|------------------|-----------------------|---------------------------|----------------------------|----------------|
| 27805 | 2014-07-12 | 823 | 5,250 | 1,673 | 135 | 1 | 1 | 2014 |
| 13372-TP | 2014-07-12 | 621 | 2,200 | 7,801 | 2,100 | 17 | 1 | 2014 |
| 24668 | 2015-07-11 | 563 | 2,900 | 2,032 | 502 | 2 | 1 | 2015 |
| 12239-TP | 2015-07-12 | 503 | 1,550 | 54,094 | 2,242 | 32 | 5 | 2015-2019 |
| 12233-TP | 2015-07-12 | 637 | 2,750 | 11,941 | 11,941 | 71 | 2 | 2015, 2019 |

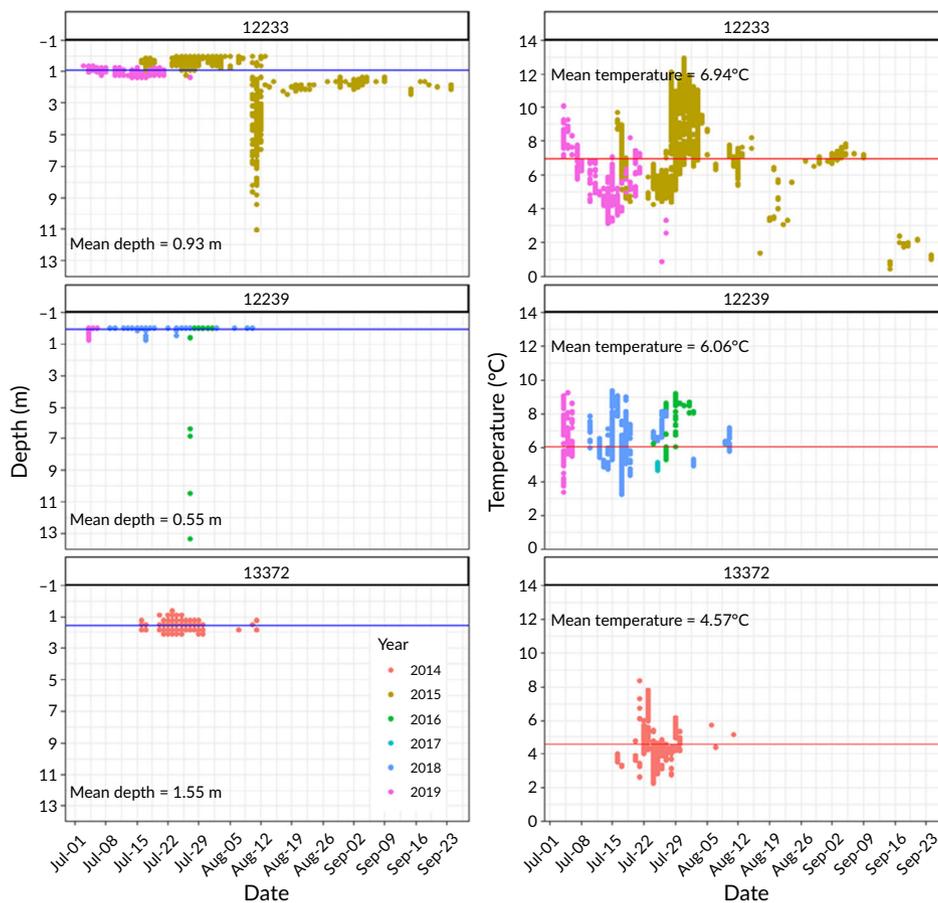


FIGURE 2 Depth and internal body temperature ($^{\circ}\text{C}$) of *S. namaycush* in the estuarine/marine environment, southern Victoria Island. Shown are all depth (left panel) and temperature (right panel) detections for each individual tagged with V16-TP acoustic transmitters. Each year of the study is represented by a different colour

individuals (Figure 2). Mean temperature calculated across all detections was 6.51°C ($\pm 2.04\text{S.D.}$), with individual *S. namaycush* ranging in mean overall body temperature from 4.57 to 6.94°C (Figure 2).

Optimal temperatures for *S. namaycush* are between 8 and 12°C (Christie & Regier, 1988), and they have a lower salinity tolerance than most anadromous salmonids (Hiroi & McCormick, 2007). Previous work has shown that estuaries in the Kitikmeot region are warmer and less saline than adjacent marine habitats, and that they are accompanied by a thin freshwater surface layer that can extend over 1 km from shore (Harris *et al.*, 2020). Therefore, *S. namaycush* likely utilize productive estuaries in this region without experiencing

significant thermal or osmotic stress. We did, however, document several detections that exceeded 10 m in depth that we presume were foraging dives (*e.g.*, Harris *et al.*, 2020). Salinity (>20) and temperature (0 – 4°C) at these depths are likely to acutely disrupt ionic and osmotic homeostasis (Hiroi & McCormick, 2007; Kissinger *et al.*, 2017), and constrain growth and metabolic performance (Christie & Regier, 1988; Gibson & Fry, 1954). Our data suggest that these dives were not prolonged and that *S. namaycush* quickly returned to warmer, lower salinity surface waters, presumably to limit the duration of exposure to suboptimal conditions and to allow for more rapid digestion (Mac, 1985). In this species, temperature is known to play an important role

in the frequency and duration of time spent in habitats used for foraging (Guzzo *et al.*, 2017). The thermal and osmoregulatory physiology of adult Arctic *S. namaycush* have not been characterized, however, and local adaptation and intraspecific diversity are prevalent within this species (Muir *et al.*, 2015). This knowledge gap leaves open the possibility that coastal Arctic *S. namaycush* are better suited to cold marine environments than their temperate counterparts. Indeed, *S. alpinus*? from populations that exhibit anadromy have a greater capacity to compensate for changes in salinity than landlocked populations (Ojima *et al.*, 2009; Bystriansky *et al.*, 2007).

In general, marine habitat use by anadromous *S. namaycush* remains poorly understood (Coad & Reist 2018). Despite small sample sizes, the results presented here provide novel insights into *S. namaycush* anadromy, including habitat use and behaviour in estuarine/marine habitats. Specifically, our telemetry results suggest they remain in estuarine habitats, prefer surface waters there and undertake estuarine/marine migrations over multiple years. Several foraging dives into deeper waters were also recorded. Our microchemistry results indicate estuarine/brackish water use (see Kissinger *et al.*, 2016) and multiple annual migrations to sea. All told, these results extend our knowledge of the distribution of anadromy in *S. namaycush* in Arctic Canada and provide some of the first insights into specific marine habitat use in this species.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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