Manuscrit à soumettre pour évaluation par les pairs

Migration patterns of Atlantic halibut in the Saguenay fjord: Insights from otolith chemistry

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Résumé

La pêche sur glace est une activité socio-économique importante dans la région du Saguenay. Au cours des dernières années, l'abondance croissante du flétan de l'Atlantique (*Hippoglossus hippoglossus*) a entraîné une augmentation des prises dans la région. Cependant, depuis 1998, tous les flétans de l'Atlantique doivent être remis à l'eau. Cette espèce présente un intérêt considérable en raison de sa valeur marchande élevée, de la qualité de sa chair et de sa taille importante, qui en font une cible pour la pêche commerciale et récréative. La population de flétan de l'Atlantique dans l'estuaire et le golfe du Saint-Laurent (EGSL) est actuellement considérée comme la plus saine et la plus importante qu'elle ait été au cours des 70 dernières années. Cela a suscité un intérêt pour la compréhension de la connectivité entre le fjord du Saguenay et l'EGSL. La chimie des otolithes, une méthode éprouvée pour étudier la migration des poissons, a été utilisée pour étudier les mouvements du flétan entre ces deux zones. Nos résultats suggèrent que, bien que certains flétans de l'Atlantique effectuent des mouvements aller-retour entre le fjord et l'EGSL, la plupart des individus qui pénètrent dans le fjord y restent. L'âge moyen auquel les flétans pénètrent dans le fjord est de quatre ans. Cette information est précieuse pour la gestion des pêches, car elle fournit une base pour quantifier l'impact potentiel de la réouverture de la saison de pêche au flétan de l'Atlantique sous la glace dans le fjord du Saguenay.

Abstract

Ice fishing is a significant socio-economic activity in the Saguenay region of Quebec. In recent years, the rising abundance of Atlantic halibut (*Hippoglossus hippoglossus*) has led to more frequent captures in the area. However, since 1998, all Atlantic halibut catches must be released back into the water. This species is of considerable interest due to its high market value, desirable flesh quality, and substantial size, making it a target for both commercial and recreational fisheries. The Atlantic halibut stock in the Estuary and Gulf of St. Lawrence (EGSL) is currently considered healthy and at its highest biomass in the past 70 years. This has sparked interest in understanding the connectivity between the Saguenay Fjord and the EGSL. Otolith chemistry, a proven method for studying fish migrations, was applied to investigate halibut movements between these two areas. Our findings suggest that while some Atlantic halibut exhibit back-and-forth movements between the fjord and the EGSL, the majority of individuals entering the fjord remain there. The average age at which halibut enter the fjord was determined to be four years old. This knowledge provides valuable insights for fisheries management, offering a basis to quantify the potential impact of reopening Atlantic halibut ice fishing in the Saguenay fjord.

Introduction

Winter recreational fishing, also known as ice fishing, is a very popular activity deeply rooted in local culture and now represents a significant source of income for the Saguenay region (Quebec, Canada). It is mainly practiced from January to March in cabins installed in fishing villages on the ice. Since 1998, an average of nearly 1500 cabins has been recorded across the different villages along the fjord (Gauthier, 2018). Nearly 60 % of these installations are dedicated to bottom-fishing species, which are the focus of a monitoring program coordinated by Fisheries and Oceans Canada (DFO) (Gauthier, 2018). During winter fishing in the Saguenay, four bottom-fish species can be legally caught and kept. In recent years, average annual catches of approximately 20 000, 1800, 1000, and 800 individuals have been recorded for redfish, Atlantic cod, Greenland cod (*Gadus ogac*), and Greenland halibut, respectively (MPO, 2019). Recruitment of groundfish in Saguenay depends on the arrival of juveniles from the St. Lawrence estuary (Gauthier, 2017). With the resurgence of Atlantic halibut in the estuary and Gulf of St. Lawrence (EGSL), catches in the Saguenay fjord are becoming increasingly common. However, since 1998, all Atlantic halibut catches must be released back into the water (Gauthier *et al.*, 2021).

Current scientific knowledge suggests that the Atlantic halibut stock in the EGSL is doing well and is at its highest abundance level in the past 70 years. Our understanding of halibut movements and their ability to thrive in a wide range of depths and temperatures suggests that halibut may migrate between the Saguenay and the EGSL, unlike redfish, which are thought to be isolated in the Saguenay due to a shallow threshold (20 m) separating the two areas (COSEWIC, 2010). Depending on the connectivity between the St. Lawrence and the fjord, recreational fishing for Atlantic halibut could lead to a short-term local decrease, and the time required for replacement by the EGSL population remains unknown.

A short-term scientific fishery has been authorized to facilitate the collection of samples for various research projects and to enhance our understanding of halibut in the Saguenay ecosystem. Otoliths, small metabolically inert calcified structures in the inner ear of fish, serve as natural biomarkers, recording environmental conditions encountered throughout a fish's life. These structures grow incrementally, preserving a chronological record of a fish's life history, which allows the reconstruction the environmental conditions experienced by an individual from hatching to capture (Campana, 1999). Otolith chemistry has been successfully used with halibut in the EGSL to track their migration patterns. Building on this expertise, the objective of this study is to assess the movements of halibut in the Saguenay using otolith chemistry, analyzing halibut samples obtained through ice fishing on the Saguenay fjord.

Methods

Sampling site and samples

The Saguenay River is part of the large Saguenay-Lac-Saint-Jean watershed. It originates from Lake Saint-Jean and flows 167 km downstream into the maritime estuary of the Saint Lawrence River. The Saguenay fjord lies between Saint-Fulgence and its mouth near Tadoussac. The fjord is divided into three basins: an upper basin upstream, which contains 75 % of the fjord’s total volume, and two smaller downstream basins, the intermediate basin and the lower basin (Drainville, 1968). The upper basin is the deepest, with a maximum depth of 276 m near Cap Trinité, while the intermediate and lower basins reach maximum depths of 180 m and 250 m, respectively (Figure 1). These three basins are separated by sills, with depths of 120 m and 60 m, respectively. A shallow sill of 20 m between the lower basin and the maritime estuary of the Saint Lawrence limits exchanges between the Saguenay and the Saint Lawrence (Drainville, 1968). The water masses in the Saguenay fjord are stratified into distinct layers. The surface layer, which ranges from 5 to 20 meters in thickness, is characterized by relatively warm and low-salinity waters (0 to 16.8°C and 0.2 to 26.9 PSU) originating from freshwater inflows from the fjord's tributaries (Belzile *et al.*, 2016; Bourgault *et al.*, 2012; Fortin & Pelletier, 1995). A strong pycnocline, located at approximately 15 meters of depth, acts as a barrier that limits mixing between the surface layer and deeper waters. Below the pycnocline, the deeper waters primarily originate from the Cold Intermediate Layer (CIL) of the EGSL. These deeper waters are cold, ranging between 0.9 and 4°C, and highly saline, with salinity levels of 27.3 to 29.8 PSU (Belzile *et al.*, 2016; Bourgault *et al.*, 2012). The winter recreational fishery occurs across the entire upper watershed of the Saguenay fjord, stretching from Saint-Fulgence to Petit-Saguenay (Gauthier, 2017).

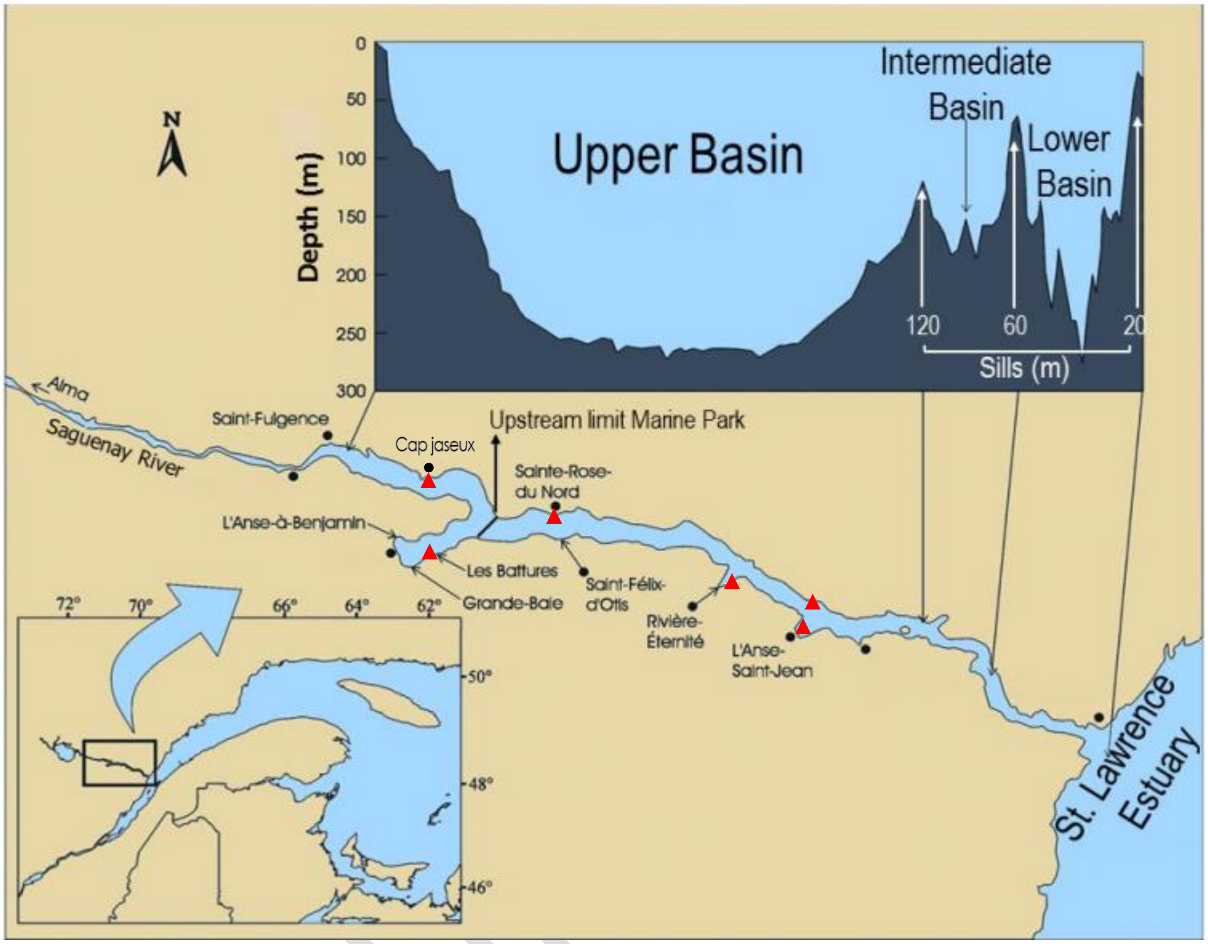

Figure 1. Map of the Saguenay fjord and the bathymetry of the three bassins. Ice fishing sites where halibut were captured are identified with red triangles. Modified from Gauthier & Marquis, 2017.

Recreational angler with a designed permit for the scientific fishery collected samples from the Saguenay fjord. The minimum legal length of 85 cm had to be respected. Biological data of length, weight, and sex were noted for each fish, and otoliths collected (Table 1). A total of 63 halibut were captured, 15 in 2023, 23 in 2024 and 25 in 2025. Otoliths were extracted and stored in individually labelled paper envelopes.

Table 1. Number of individuals and information captured in the Saguenay fjord per sampling year and sex, presented as mean ± standard deviation (SD).

Year of capture	Sex	Mean fish length (cm)	Mean fish weight (kg)	N
2023	F	129.7 ± 23.5	28.4 ± 15.2	13
2024	F	151.3 ± 16.1	39.7 ± 13.9	22
	M	126.0	22.5	1
2024	F	154.2 ± 21.1	45.4 ± 16.7	25

Otolith chemistry data of halibut from the EGSL captured in 2017 and 2018 by Gauthier *et al.* (2024) were used to compare the Saguenay to the EGSL. Briefly, 187 Atlantic halibut were sampled throughout the EGSL in July to October of 2017 and 2018 during fishery-independent research trawl surveys carried out in the northern and southern GSL by the Department of Fisheries and Oceans Canada (DFO), during trawl mobile sentinel survey, and during longline and gillnet commercial fisheries. Otoliths were extracted and stored in individually labelled paper envelopes.

Otolith preparation

All manipulations were made to avoid metal contamination of otoliths. Otoliths were cleaned and stored in polyethylene vials and dried under a laminar flow hood (> 24 hours). Left sagittal otoliths were selected when available because they are known to show clearer growth rings (Karlson *et al.*, 2013). If the left otolith was missing or broken, the right one was used. Otoliths were embedded in Epoxy resin (Miapoxy 100, Freeman, OH, USA) and the position of the core was identified under binocular microscope and marked. Otoliths were then sectioned through the core using a low-speed saw with a diamond blade (IsoMet saw; Buehler, IL, USA) to obtain 600 µm thick transverse cross sections and expose the core. Each section was polished to smooth the surface, using aluminum oxide polishing (1200 µm grade, 3 M™) and lapping films (1- and 5-µm grade, 3 M™). Polished sections were fixed on petrographic slides with thermoplastic glue (CrystalbondTM509; AremcoTM products, NY, USA). The slides were ultrasonically bathed in ultrapure water for five minutes three times, before being dried under a laminar flow hood and then stored until further processing.

Otolith laser ablation

Trace element analyses were carried at Earth's Materials Laboratory (LabMaTer) at the University of Quebec at Chicoutimi using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS; Agilent 7700× ICP-MS coupled to a Resonetics Resolution M-50 Excimer 193 nm ArF laser). Otoliths were ablated according to their randomly generated order. Transects were ablated on the dorsal axis, from before the core, going through the core until reaching the edge of the otolith, representing approximately 2/3 of the otolith cross section length. Each ablation used a beam diameter of 33 µm, laser fluence of 5 J·cm^{-2}, a repetition rate of 30 Hz, and a travelling speed of 10 µm·s^{-1}. The gas mix carrying ablated material into the ICP-MS was composed of an Argon-Helium gas mix at a rate of 0.8^{-1} L min^{-1} for Argon and 350 mL min^{-1} for Helium. Nitrogen was also added to the mixture at a rate of 2 mL min^{-1}. The chosen parameters provide a temporal resolution of approximately one week per second of ablation, considering that the resolution decreases towards the end of the transect due to slower growth and the closer spacing of annual growth increments (Høie *et al.*, 2004; Kastelle *et al.*, 2017). A total of 35 elements isotopes, representing routine otolith analyses in LabMaTer, were targeted for quantification (^{7}Li, ^{11}B, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{27}Al, ^{29}Si, ^{31}P, ^{34}S, ^{39}K, ^{42}Ca, ^{43}Ca, ^{44}Ca, ^{55}Mn, ^{56}Fe, ^{57}Fe, ^{59}Co, ^{60}Ni, ^{61}Ni, ^{63}Cu, ^{64}Zn, ^{65}Cu, ^{66}Zn, ^{69}Ga, ^{85}Rb, ^{86}Sr, ^{87}Sr, ^{88}Sr, ^{118}Sn, ^{119}Sn, ^{120}Sn, ^{136}Ba, ^{137}Ba, ^{138}Ba, ^{202}Hg and ^{206}Pb).

A 30 s gas blank acquisition preceded each ablation for background correction. NIST-610, USGS MACS-3 and GP-4 were used as reference materials and were ablated for 60 s approximately every hour (roughly every 5 samples). To standardize the element concentrations, samples were normalized to the ^{43}Ca standard of 38.02 % as recommended by Campana (1999) and expressed as concentration ratios in mmol·mol^{1} units for each element (element:Ca ratios). Limits of detection (LOD) were calculated for each element by dividing three times the standard deviation of the gas blank by the sensitivity of the signal, as described by Lazartigues *et al.* (2014). Element concentrations that fell below the LOD were excluded. Additionally, data points consistent with contamination from CrystalBond thermoplastic glue (i.e., ^{29}Si, ^{31}P, and ^{34}S) were removed, as well as any data points with low ^{44}Ca concentration, which could indicate cracks or irregularities in the otolith matrix, along the transect. Only ^{24}Mg, ^{88}Sr and ^{138}Ba were over LOD at least 50 % of the time and could be linked to spatial difference. Hence, they were the three elements considered for further analysis. To simplify, no mass numbers will be included in the following text, for example, Mg will be used instead of ^{24}Mg.

Age readings

Age readings were done by visual examination of whole otoliths and mounted otolith transverse cross sections (Figure 2). Whole otoliths were photographed using the 4K high-resolution optical imaging system Keyence VX-700 before sectioning the otoliths. Both visuals were combined to arrive to a more precise age estimate. Pictures of otoliths sections were taken with Leica M125C and modified in Photoshop (version 23.5.1, Adobe, Inc.) to adjust luminosity and contrast, making annuli more visible. Distances between annuli on sections were compiled using software ImageJ (Schneider *et al.*, 2012). Otoliths were examined without any knowledge of the length of otoliths or individuals. The first annuli was identified using visual reading and validated by looking at Mg profiles, where the first drop of Mg coincided with the mark of the first winter. The concentration of Mg reflects seasonal variations in growth and similar chemical patterns have been observed in Atlantic cod (*Gadus morhua*) (Hüssy *et al.*, 2021; Limburg *et al.*, 2018). Two independent readers performed all age readings. When readings differed between readers, a common reading was assessed. If a consensus could not be reached, otoliths were rejected (4.9 % of rejection rate).

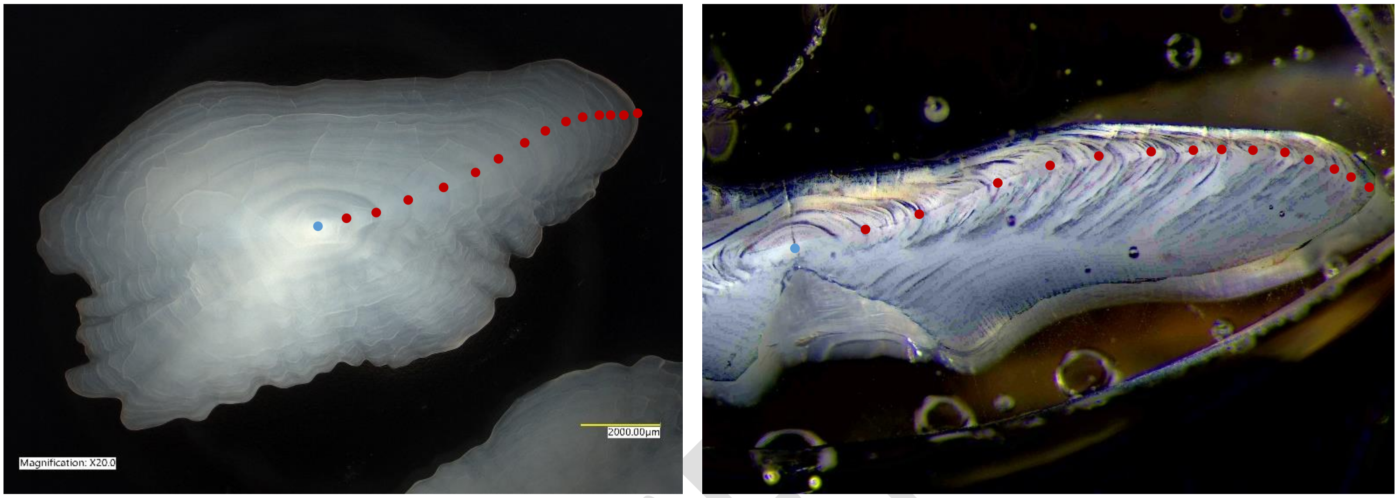

Figure 2. Age readings of whole otolith and otolith sections. The picture of the otolith section was enhanced in Photoshop to highlight contrasts. The blue dot marks the primordium and subsequent red dots mark the annual increments. The estimated age is 14 years old.

Condition index

Fish condition was assed using Fulton's K condition factor, calculated by dividing body weight by the cube of body length, then multiplying by a scaling constant. Fish Fulton's K index was compared between contingents using a Student's t-test, following verification of equal variances with Levene's test.

Differencing chemical signatures of the Saguenay from the EGSL

Prior to analysis, the distance between consecutive annuli was used to adjust chemical transects proportionally to increments width as done in Gauthier *et al.* (2024). To assess the effect of growth on element incorporation and avoid confounding any site-specific differences in otolith chemistry, the relationship between element:Ca ratios in edges and fish age was evaluated using

Generalized Additive Model (GAM) and verifying the significance of the trend. The relationship was significant for Sr:Ca (positive relationship, adjusted $r^2 = 0.53$, $P < 0.0001$) and Ba:Ca (positive relationship, adjusted $r^2 = 0.16$, $P < 0.0001$). We assessed the ontogeny effect by sustracting the curve of the GAM from every individual transect to remove the changes in element incorporation that would be linked to ontogeny and leave variations linked with environmental changes.

The last 40 µm of transects were used as edges to represent chemical signature of the sampling site (Sag or EGSL). We assumed that the last month of the fish's life would have been spent around the capture site as halibut in the EGSL remains in the same area during fall (Gatti *et al.*, 2020). Element data was analysed for normality and homogeneity of variance, and where conditions were met student's t-test was used, otherwise we used Mann-Whitney U test. To evaluate the differences between zones, a Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted on the Euclidean distance matrix of the scaled data. This approach accounts for non-normality in the data and scaling the data ensures that all elements contribute equally to the analysis.

Describing movement patterns between the Estuary and Gulf of St. Lawrence and the Saguenay fjord

To identify transitions between habitats along chemical transects, we used Split-Moving Window analysis (SMW) (Gauthier *et al.*, 2024; Morissette *et al.*, 2016; Vanalderweireldt *et al.*, 2019). SMW were performed on principal components (PC) of Mg, Sr and Ba data for each transect of halibut captured in the Saguenay fjord. The number of PCs was determined by the "eigenvalues equal one" rule (Quinn & Keough, 2002). Window width was chosen based on autocorrelation analysis to correspond to approximately 2/3 of the distance between transitions (Webster, 1973). As mentioned above, transects were made proportional to age to facilitate the detection of limits towards the end of life when annuli are closer to each other. This transformation changed the density of data points along the x axis, with less data points per year as growth slows down with age. To assess this change in point density and its effect on SMW, two significance thresholds were defined, one before the mean age at maturity, and one after. Maturity was chosen as a breaking point since growth starts to decrease significantly after reaching maturity when energy starts being allocated to reproduction (DFO, 2023). Therefore, before age 10, habitat transitions were considered significant when the Mahalanobis distance was greater than the mean distance before age 10 plus one standard deviation (SD) and the same method was applied for the rest of the transect after age 10. SWM was performed using the smw.R procedure (Rossiter, 2013). Each segment between transitions represented time spent in a chemically stable environment. Mean values of each element were calculated for each segment to represent the habitat chemical fingerprint. Segments between transitions were assigned to one of two zones based on edge fingerprints using discriminant function analysis (DFA). Priors were set according to the proportion of individuals from the Saguenay and the EGSL to account for any imbalance in the data. With SMW, the first and last half windows represent blind spots in the analysis (Panis & Verheyen, 1995). Halibut from both the Saguenay and EGSL exhibited a peak in Ba concentration approximately 1000 µm from the otolith core or around 2 years old (Figure S1). This elevated Ba concentration is believed to be ontogeny-related rather than environmentally driven. Since Ba is the primary element distinguishing the Saguenay chemical fingerprint, and it is known that halibut recruitment occurs outside the Saguenay, the two years of life were excluded from the analysis. All statistical analyses were performed in R (R Core Team, 2022).

Results

Differences in chemical fingerprints between zones

Using Mg:Ca, Sr:Ca and Ba:Ca in otolith edges, we observed significantly different chemical signatures in the EGSL and the Saguenay (PERMANOVA, $F_{1,\,201} = 20.269$, $P < 0.001$). Concentrations of Sr ($t = -2.0254$, $df = 47.7$, $P = 0.048$) and Ba ($W = 816$, $P < 0.001$) varied significantly between the two zones, whereas the concentrations of Mg did not show significant variation ($W = 3034$, $P = 0.2123$) (Figure 3). The Saguenay signature was characterized by slightly higher Sr:Ca concentrations and substantially higher Ba:Ca concentrations compared to the EGSL signature.

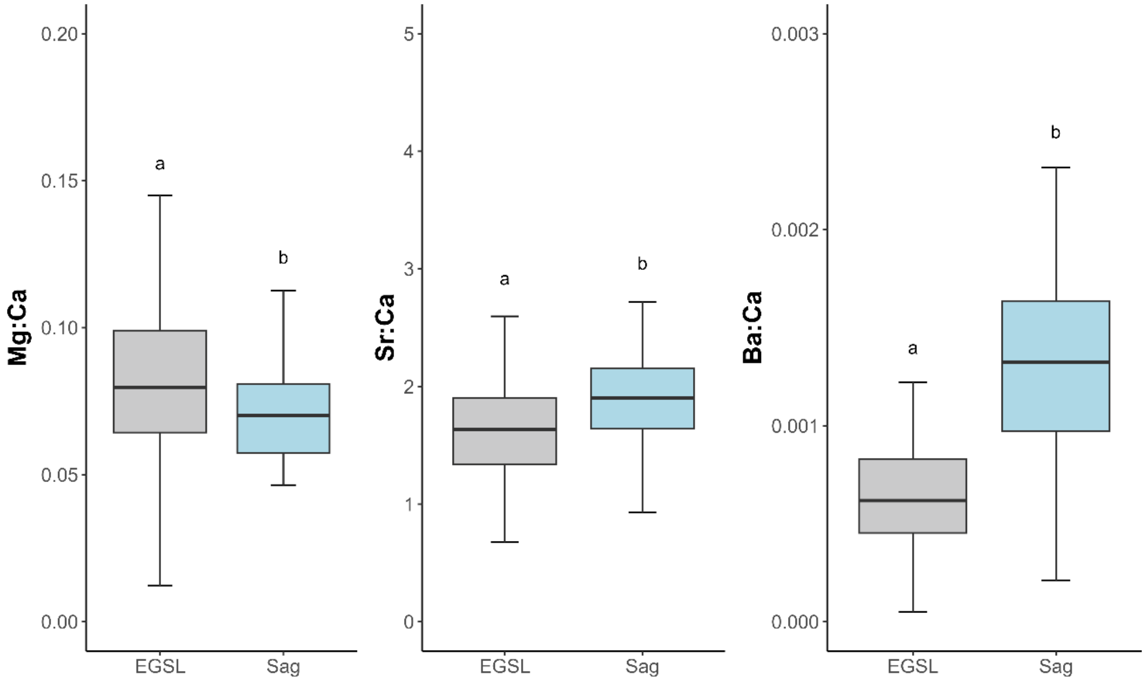

Figure 3. Element concentrations (ratio element:calcium) measured in the otolith edges of Atlantic halibut by sampling sector. The solid line inside of the box indicates the median, error bars show the standard deviation. Sr and Ba have been corrected to remove the effect of age. Letters indicate significant differences ($P < 0.05$).

Movement patterns between the Estuary and Gulf of St. Lawrence and the Saguenay fjord

SMW analysis was performed on principal components (PC) of adjusted transect data. The first two PCs for each individual explained 91.9 ± 7.7 % (mean ± SD) of the variation on average. Window widths for SMW were set individually and had an average of 27.5 ± 12.6 units (mean ± SD), ranging from 7 to 51.

Three main migratory patterns were observed (Figure 4). The majority (53 %) of fish that transitioned from the EGSL to the Saguenay remained in the fjord for the rest of their lives. A proportion of 32% of individuals moved back into the EGSL after entering the Saguenay. This included one (22%), two (7%) and more than two (3%) trips back into the EGSL. Some fish were not reassigned to the Saguenay, even if they were captured there (15%).

The average age at which halibut entered the Saguenay is 4.2 ± 3.0 years old, with most fish making the transition between 2 and 3 years of age. The oldest recorded entry into the Saguenay occurred at 13 years of age. No significant differences of Fulton’s condition index were found between the Saguenay and the EGSL ($P > 0.05$).

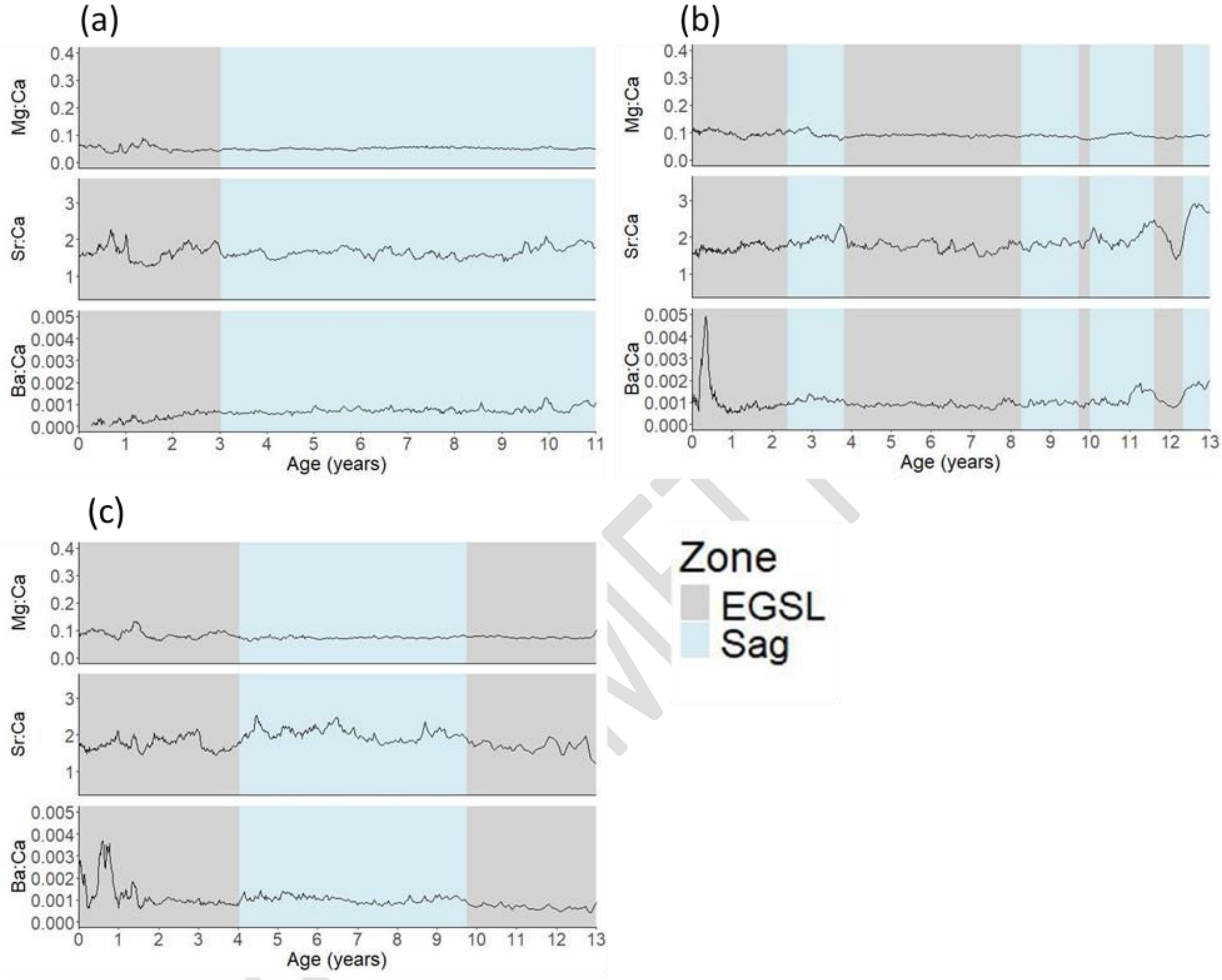

Figure 4. Chemical profiles of examples of the three observed recurring patterns. (a) Residency in the Saguenay after entry. (b) Movements between the Saguenay fjord (Sag) and the Estuary and Gulf of St. Lawrence (EGSL). (c) Ending not reassigned to the Saguenay.

Discussion

We used otolith chemistry to identify a distinct signature in the Saguenay fjord, incorporated into the otoliths of Atlantic halibut, and used this signature to track movements between the Saguenay and the EGSL throughout the halibut's life.

Chemical differences between the Saguenay fjord and the estuary and Gulf of St. Lawrence

The chemical fingerprint of the Saguenay was primarily differentiated by higher Ba concentrations compared to the EGSL. Ba concentrations in otoliths are mainly influenced by environmental factors (Thomas *et al.*, 2017). Ba originates from freshwater sources and is known to be negatively correlated with salinity (Walther & Thorrold, 2006). The influx of freshwater into the Saguenay fjord likely explains the higher Ba concentrations observed in its fingerprint. While the fingerprints were collected at different time periods—2017-2018 for the EGSL and 2023-2025 for the Saguenay—any potential temporal variation is considered unlikely to significantly affect the results, as the physicochemical conditions in both environments are quite distinct.

Migrations

Migration is known to be a frequent behavior for halibut in the EGSL (Gatti *et al.*, 2020; Gauthier *et al.*, 2024), with density dependence and feeding as the main hypothesised drivers. Halibut may wander into the Saguenay in search of areas with better prey availability and lower density. The Saguenay is known to provide advantageous habitat for Atlantic cod, which exhibits better condition indices there than in the EGSL. For the same length and time of year, cod from the Saguenay have higher weight and hepatosomatic indices compared to those from the EGSL during winter (Gauthier *et al.*, 2019; Richard, 1997). This improved condition could be due to the fact that cod in the Saguenay can feed year-round in the deep water layer, while cod in the EGSL must migrate between spawning and feeding grounds, limiting their ability to feed during the winter

(Gauthier *et al.*, 2019; Richard, 1997). A similar explanation may apply to halibut. While halibut can remain in the deep water layer and feed all year round, shallower waters are hypothesised to act as advantageous feeding grounds in summer (Gauthier *et al.*, 2024), and the Saguenay could offer a similar habitat. We found no differences in condition index between the Saguenay and the EGSL, but both were over 1, indicating overall good condition.

Gauthier *et al.* (2024) showed that halibut from the EGSL tend to migrate between shallow and deep waters during the first three years of their life, after which the majority become residents of the deep waters. This timing aligns with our findings, where the average age of entry into the Saguenay is around four years old. Halibut entering the Saguenay later are likely migrants from the EGSL. Residency being a common behavior in the EGSL, it is consistent with the majority of halibut in the Saguenay remaining in the fjord for the rest of their lives once they enter. However, irregular migrants have been described, where individuals alternate between migrating and residency periods (Gauthier *et al.*, 2024), suggesting that it remains possible for halibut from the Saguenay to return to the EGSL. Halibut that make multiple entries into the Saguenay display behavior more similar to that of migrants.

We observed that some individuals were simply not reassigned to the Saguenay for their whole life. This could be explained by the fact that they entered the Saguenay too recently for the chemical fingerprint to be incorporated into their otoliths. The lag can be from weeks to months, varying at a species and an individual level (Vignon *et al.*, 2023). The Ba correction could also explain why the last section of the transect was not reassigned to the Saguenay. While the correction was necessary to remove the trend with age, ontogenetic effects may vary between individuals, potentially resulting in lower Ba values towards the end of life (Macdonald *et al.*, 2020). Since high Ba levels in the Saguenay primarily influence the fingerprint, individuals with overcorrected Ba values may have been misclassified as belonging to the EGSL (Figure S1). However, this scenario is considered to have a low occurrence and does not meaningfully affect the interpretation of the results.

Connectivity

It is recognized that there is connectivity between the Saguenay and the EGSL. Indeed, genetic studies on redfish, Atlantic cod, and Greenland halibut, have highlighted that the populations of the Saguenay are not genetically distinct from those of the EGSL (Carrier *et al.*, 2020; Ferchaud et al., 2022; Roques *et al.*, 2002; Sévigny *et al.*, 2009; Sévigny, 1994; Valentin *et al.*, 2014). However, other studies have noted phenotypic differences between these populations, such as in the parasitic fauna of Greenland halibut (Arthur & Albert, 1993), in the elemental composition of cod and redfish otoliths (Campana *et al.*, 2007; Sévigny *et al.*, 2009), and in the morphometric of redfish (Valentin *et al.*, 2014). These phenotypic differences suggest that these populations in the Saguenay spend the majority of their life cycle within the Saguenay. The Saguenay would thus harbor sink populations whose recruitment depends on the entry of juveniles from the EGSL (Bui *et al.*, 2012; Sirois *et al.*, 2009).

It is well established that recruitment to the Saguenay's groundfish population primarily comes from the EGSL, as there is no evidence of reproduction occurring within the Saguenay, and the surface freshwater layer presents conditions that are inhospitable for marine fish larvae. Our findings reveal that, unlike other groundfish species in the Saguenay, Atlantic halibut exhibit some movement between the two habitats, though this movement is infrequent.

Implications for management

The Saguenay may not function as a sink population, as there appears to be some movement between the Saguenay and the EGSL, unlike what is seen with species such as redfish and cod. However, the most common behavior observed seems to be that Atlantic halibut remain in the Saguenay once they have entered. A healthy EGSL stock could facilitate the regular renewal of the Saguenay's population. Our results suggest that once a halibut enters the Saguenay, its chances of contributing again to the recruitment of the EGSL stock in subsequent years are low. We have to keep in mind that our analysis was based only on individual's captured in the Saguenay. Therefore, halibut that would have visited to Saguenay but left before being capture are not accounted for in our conclusions. But since most halibut from the Saguenay displayed a residency behavior, we estimate that the impact on our conclusions is minor.

Supplementary material

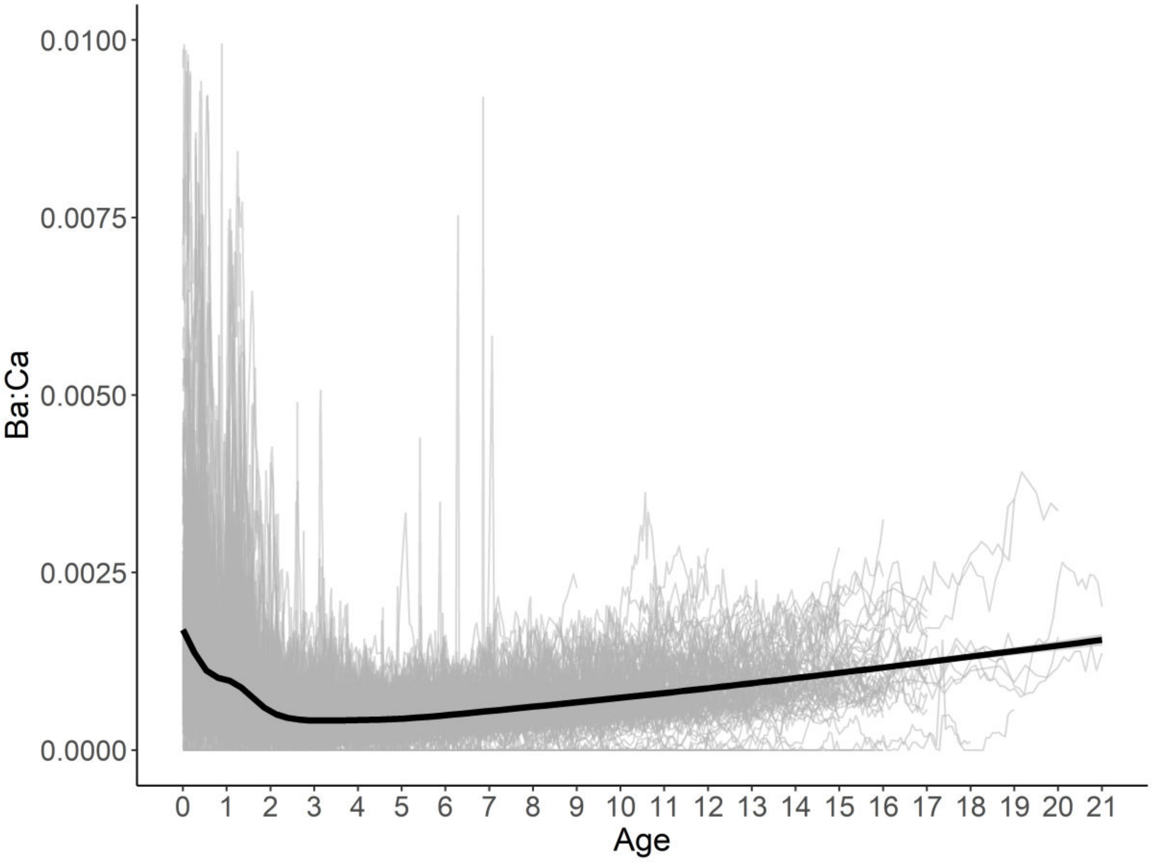

Figure S1 Concentrations of Ba:Ca along otolith transects by age, with elevated levels observed around 2 years of age. Each line represents an individual otolith transect, with a smoothed GAM trendline (black line) highlighting the overall pattern across all samples.

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