

Spatiotemporal variability in otolith core elemental fingerprints to assess natal origin of Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence

Charlotte Gauthier^a, Jonathan A.D. Fisher^b, Dominique Robert^c, and Pascal Sirois^b

^aDépartement des sciences fondamentales, Université du Québec à Chicoutimi, Chicoutimi, Canada; ^bCentre for Fisheries Ecosystems Research, Fisheries and Marine Institute, Memorial University of Newfoundland, St. John's, Canada; ^cInstitut des sciences de la mer, Université du Québec à Rimouski, Rimouski, Canada

Corresponding author: **Charlotte Gauthier** (email: charlotte.gauthier1@uqac.ca)

Abstract

Early life stages play a critical role in shaping recruitment dynamics and population structure in marine fishes, with implications for conservation and resource management. After declining in the 1950s, Atlantic halibut (*Hippoglossus hippoglossus* (Linnaeus, 1758)) in the Gulf of St. Lawrence (GSL), Canada, has shown a marked comeback since the early 2000s, now ranking as the most valuable groundfish resource. Given its socio-economic importance, understanding larval ecology and early life stages is key to sustainable management. Spawning occurs in deep GSL channels and individuals exhibit summer site fidelity. Recently, otolith chemistry provided insights into lifetime movements and revealed three migratory contingents: annual migrants, irregular migrants, and residents. We analyzed the cores of 187 otoliths from halibut with known migration histories using laser ablation inductively coupled plasma mass spectrometry to quantify the number of nurseries and their contributions to the stock. To assess temporal trends, we examined four cohorts (2006, 2007, 2009, and 2010). Our findings suggest that Atlantic halibut in the GSL forms a philopatric population with multiple nurseries, and that natal origin does not influence later migration strategies. Given the role of early life stages in stock recruitment, these insights enhance our understanding of natal sources and support more informed management strategies.

Key words: otolith chemistry, connectivity, natal origin, *Hippoglossus hippoglossus* (Linnaeus, 1758), LA-ICP-MS, Gulf of St. Lawrence

Introduction

Effective fisheries management relies on a clear understanding of stock structure and mixing as it provides information on essential habitat and helps evaluate the impacts of fishing on stock dynamics (Goethel et al. 2011; Cadrin 2020). Delineating fish stocks, identifying nursery areas and their contribution to the stocks and understanding the migration patterns among habitats provides the foundation for robust management policies across interconnected areas (Morales et al. 2010; Cadrin 2020). Connectivity, defined by both passive and active demographic exchanges between groups of individuals across spatially structured habitats or regions, profoundly influences the structure, dynamics, and resilience of fish populations under increasing anthropogenic pressures (Thorrold et al. 2001; Cowen and Sponaugle 2009). In marine fish, larvae and other early-life stages are known to have a high dispersion capacity and therefore play important roles in connectivity (Cowen et al. 2007; Pineda et al. 2007; Cowen and Sponaugle 2009). An essential step in understanding connectivity is determining the natal origins of adult individuals, a critical aspect that remains unknown for many species

(Cowen et al. 2007). The conditions experienced in early life can also lead to subsequent different life strategies, such as different migration patterns and growth rates, emphasizing their effect on the structure and productivity of the population (Morrison et al. 2021; Wu et al. 2023).

Otoliths have emerged as invaluable tools in connectivity studies due to their ability to serve as archival tissues. Composed predominantly of calcium carbonate, otoliths grow continuously throughout a fish's life and retain chemical signatures that reflect the environmental conditions the fish experiences. These signatures, which include trace elements and isotopes, provide a natural record of habitat use and migration patterns (Campana 1999; Avigliano and Volpedo 2016). Otoliths are metabolically inert, preserving their chemical composition over time (Campana and Neilson 1985). This stability makes them a reliable archive of life history, allowing researchers to trace the natal origins of individuals and understand stock dynamics (Elsdon et al. 2008; Rooker et al. 2014). The chemical composition of otoliths is influenced by the surrounding water's geochemistry, creating area-specific chemical fingerprints (Walther and Limburg

2012). For example, strontium has proven particularly useful in tracking fish migrations across salinity gradients, serving as a proxy for environmental conditions (Limburg 1995; Panfili et al. 2015). In fully marine environments, the ability to distinguish fingerprints depends on the magnitude of spatial variation in seawater chemistry, which requires sufficient contrast between regions or water masses (Sturrock et al. 2012). Otolith chemistry has also proven to be a valuable tool for identifying nursery areas and understanding stock structure in various marine fish species (Rooker et al. 2014; Tanner et al. 2016; Biolé et al. 2019). While some variability in elemental incorporation can arise from physiological or dietary factors (Doubleday et al. 2013; Sturrock et al. 2015), the ability of otoliths to track spatial differences and provide crucial data on habitat use and migration emphasizes their importance in advancing sustainable fisheries management.

Atlantic halibut (*Hippoglossus hippoglossus* (Linnaeus, 1758)), a large cold-water flatfish found in the Northwest Atlantic (Haug 1990), is particularly abundant in Canadian waters, where males can reach around 189 cm and females up to 300 cm (Trumble et al. 1993; Sigourney et al. 2006; Ray et al. 2016). In the Gulf of St. Lawrence (GSL), Atlantic halibut is currently the groundfish species with the highest landings value (Government of Canada 2022). The GSL stock crashed in the 1950s after years of high abundance, largely due to overfishing (Archambault and Grégoire 1996; Armsworthy and Campana 2010). Following several decades of low abundance, the stock has seen a remarkable recovery with landings exceeding 1500 tons in 2022, the highest in over 60 years (DFO 2023). Halibut is a long-lived species (38–50 years) with females maturing at larger sizes (103–125 cm) and older ages (7–13 years) than males (55–80 cm, 5–12 years) (Armsworthy and Campana 2010; Armsworthy et al. 2014). Recent tagging studies using pop-up satellite archival tags (PSAT) have provided new insights into adult halibut movements and reproductive behaviours. Summer site fidelity, defined as the repeated return of individuals to a specific area during summer, has been observed, along with spawning activity from December to April in the GSL's deep channels (Murphy et al. 2017; Gatti et al. 2020; Marshall et al. 2023). After spawning, the pelagic period of larvae is estimated to last 6–7 months, after which metamorphosis into flatfish occurs at sizes of 17–45 mm (Zwanenburg 1991; Kvenseth et al. 1996; Solbakken and Pittman 2004). Although highly informative, PSATs are limited to large individuals and provide information for only one seasonal cycle, leaving major gaps in knowledge of early life stages and juvenile habitats (Hanson et al. 2022). Notably, there is very little information on their habitat use during the first 2 years of life, before they reach ~30 cm and are detectable in annual trawl surveys (Bourdages et al. 2019). To date, halibut eggs have never been collected in the GSL, and larvae have only been observed once, while nursery habitats for early juveniles remain unknown (Ghinter et al. 2023). Previous work using otolith chemistry to reconstruct lifetime migrations in Atlantic halibut identified three distinct migratory contingents: annual migrants, irregular migrants, and residents (Gauthier et al. 2024). These contingents reflect varying degrees of site fidelity and mobility among individuals. However, that research focused on post-recruitment

life stages and did not investigate the early dispersal phase, leaving uncertainties about how initial natal origins relate to later movement behaviour.

Otolith chemistry provides a powerful tool to address these knowledge gaps by offering a natural, lifelong archive of a fish's environmental and physiological history. This technique allows for the reconstruction of migration patterns and habitat use throughout a fish's lifespan (Reis-Santos et al. 2023), making it particularly valuable for species like halibut in the GSL, where early life stages are difficult to sample. This study aims to quantify the number of natal origins and their contributions to the stock using chemical signatures in otolith cores. Additionally, by having access to otoliths from halibut with known migratory history (Gauthier et al. 2024), we also aim to assess the link between natal origin and migration contingent. Considering the lack of genetic structure in the stock (Kess et al. 2021), we hypothesize that natal sources may provide recruits to multiple regions and cohorts within the GSL, while natal origins may influence later migration behaviours and movement patterns.

Materials and methods

Sampling site and samples

In Canada, Atlantic halibut is managed as two distinct stocks: the GSL stock, covering Northwest Atlantic Fisheries Organization (NAFO) Divisions 4RST (Fig. 1), and the southern Grand Banks-Scotian Shelf stock, encompassing NAFO Divisions 3NOPs4VWX5Zc. The GSL, a semi-enclosed sea with diverse oceanographic conditions, is strongly influenced by the freshwater inflow of the St. Lawrence River (Galbraith et al. 2024). It connects to the Atlantic Ocean via the Cabot Strait and the Strait of Belle Isle. The Laurentian Channel, the deepest part of the GSL (150–540 m), extends west to east, effectively dividing the GSL into northern and southern regions. The northern GSL features two other deeper channels, the Esquiman and Anticosti Channels, while the southern GSL consists of a shallow plateau with an average depth of 80 m (Koutitonsky and Bugden 1991).

During the summer, the GSL is made up of three distinct water layers: the surface layer (<75 m), the cold intermediate layer, and the deep-water layer (>150 m) (Galbraith et al. 2024). The surface layer, influenced by air temperature, shows highly variable conditions over a seasonal cycle, with temperatures ranging from freezing (January–March) to almost 20 °C in shallow sectors during summer. Salinity varies from 27 to 32 psu throughout the GSL. The cold intermediate layer is usually defined as the part of the water column that is colder than 1 °C with salinities of 32–33 psu (Smith et al. 2006). The deep-water layer is characterized by temperatures ranging from 1 to >7 °C and salinities between 32.5 and 35 psu. On average, temperature and salinity increase with depth, and little mixing occurs between the deep-water layer and upper layers, resulting in water masses with distinct physical and chemical properties (Galbraith et al. 2024).

Atlantic halibut were sampled throughout the St. Lawrence Estuary and GSL in July to October of 2017 and 2018 (Fig. 1). Species identification was based on distinctive external

Fig. 1. Sampling locations for Atlantic halibut (*Hippoglossus hippoglossus*) collected in 2017 (blue circles) and 2018 (yellow squares) in the Gulf of St. Lawrence. The grey line indicates the 100 m isobaths and the shaded grey area represents water deeper than 200 m. NAFO divisions are identified in red. Isobaths come from the NONNA database, Canadian Hydrographic Service, Fisheries and Oceans Canada 2023; map is in NAD83/Statistics Canada Lambert projection, EPSG:3347.

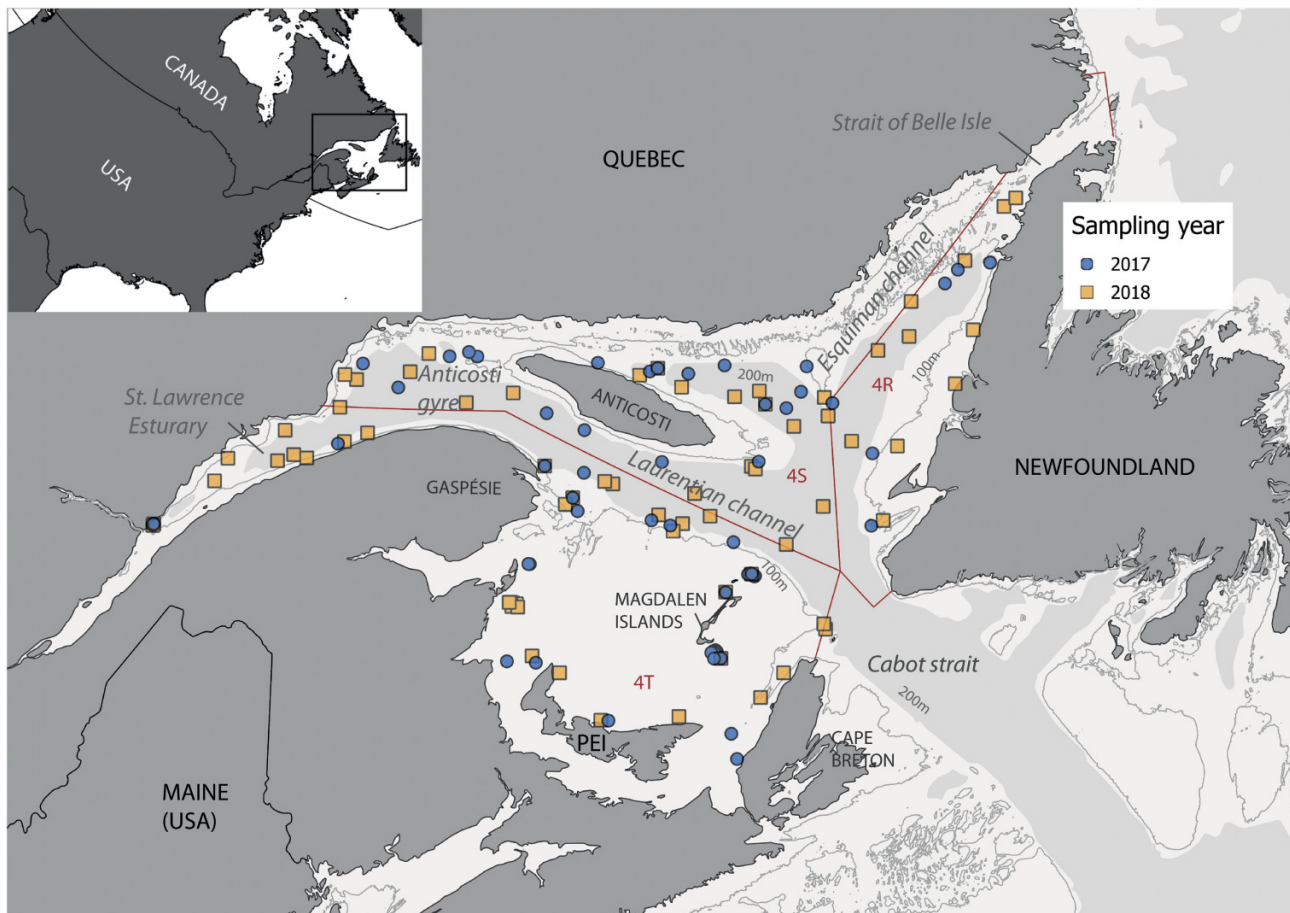


Table 1. Number of Atlantic halibut (*Hippoglossus hippoglossus*) and information at capture per sampling year and sex, presented as mean \pm standard deviation.

Year of capture	Sex	Mean fish length (cm)	Mean capture depth (m)	N
2017	M	101.0 \pm 20.9	165.7 \pm 119.6	46
	F	126.9 \pm 31.8	119.8 \pm 102.0	59
2018	M	101.2 \pm 19.2	190.9 \pm 115.6	46
	F	110.4 \pm 26.4	141.8 \pm 109.8	36

morphology. We used otoliths from 187 halibut that were either caught during fishery-independent research bottom trawl surveys carried out in the northern and southern GSL by the Department of Fisheries and Oceans Canada (DFO), during bottom trawl mobile sentinel survey, and during longline and gillnet commercial fisheries. Sampling covered the entire management unit (4RST). Fork length, sex, average tow depth, tow number, and catch geographic coordinates were recorded for each individual analyzed (Table 1). Migration histories were available from a previous study that determined whole-life migration patterns using otolith chemistry from

transects (Gauthier et al. 2024). Otoliths were extracted and stored in individually labelled paper envelopes. As this study used biological material from fish already captured through scientific surveys and commercial fisheries, no animal care approval was required.

Otolith preparation and ablation

Otolith preparation procedures followed those described in Gauthier et al. (2024), including cleaning, resin embedding, and sectioning to expose the core prior to ablation. Trace element analyses were carried at Earth's Materials Laboratory

(LabMaTer) at University of Quebec at Chicoutimi using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS; Agilent 7900× 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. Data from the first 300 µm after the middle of the core were used to represent core fingerprint. 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. A total of 35 elements isotopes, representing routine otolith analyses in LabMaTer, were targeted for quantification (⁷Li, ¹¹B, ²³Na, ²⁴Mg, ²⁵Mg, ²⁷Al, ²⁹Si, ³¹P, ³⁴S, ³⁹K, ⁴²Ca, ⁴³Ca, ⁴⁴Ca, ⁵⁵Mn, ⁵⁶Fe, ⁵⁷Fe, ⁵⁹Co, ⁶⁰Ni, ⁶¹Ni, ⁶³Cu, ⁶⁴Zn, ⁶⁵Cu, ⁶⁶Zn, ⁶⁹Ga, ⁸⁵Rb, ⁸⁶Sr, ⁸⁷Sr, ⁸⁸Sr, ¹¹⁸Sn, ¹¹⁹Sn, ¹²⁰Sn, ¹³⁶Ba, ¹³⁷Ba, ¹³⁸Ba, ²⁰²Hg, and ²⁰⁶Pb).

To standardize the element concentrations, samples were normalized to the ⁴³Ca 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. Data points exceeding three standard deviations over or under the mean were considered outliers and replaced by the mean of the precedent and subsequent value. Only ²⁴Mg, ⁸⁸Sr, and ¹³⁸Ba were over LOD at least 50% of the time and could be linked to spatial differences. 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 ²⁴Mg. Additional details on ablation procedures are available in Gauthier et al. (2024).

Age readings

Age readings were done by visual examination of mounted otolith transverse cross sections. Pictures of sections were taken with a Leica M125C microscope and modified in Photoshop (version 23.5.1, Adobe, Inc.) to adjust luminosity and contrast, making annuli more visible. Distances between annuli were compiled using software ImageJ (Schneider et al. 2012). Otoliths were examined without any knowledge of the length of otoliths or individuals. The first annulus was identified using visual reading and validated by looking at Mg profiles, where the first drop in Mg concentration 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* (Limburg et al. 2018; Hüsey et al. 2021). All age readings were performed by two independent readers. When readings differed between readers, a common reading was assessed. If a consensus could not be reached, otoliths were rejected (5.6% rejection rate). The last growth increment was not counted as a full year since fish were captured at the end of summer or fall, and spawning occurs in winter (Gatti et al. 2020).

Data analysis

Each element:Ca ratio was tested for normality and homogeneity of variance. If, even after transformation, data did not meet the assumptions, nonparametric tests were used for the following analysis.

Spatial and temporal variations in core fingerprints

Since the average first winter ring is around 600 µm (Armsworthy and Campana 2010; Gauthier et al. 2024), we defined the core area as the first 300 µm. Keeping in mind that temporal effects might affect chemical concentrations over years, we analyzed core data of all halibut sampled together to extract broad tendencies. Unsupervised random forests were performed as a clustering analysis (Shi and Horvath 2006) on the otolith core elemental fingerprint to gain insights into the number of natal sources contributing to the GSL. Unsupervised methods do not rely on prior data and aim to uncover patterns or classifications rather than making predictions (Shi and Horvath 2006). This unsupervised clustering approach has successfully been used to investigate natal origins when the locations of larval sources are unknown (Gibb et al. 2017; Wright et al. 2018; Artetxe Arate et al. 2019; Pan et al. 2020), even in the GSL, with redfish (Coussau et al. 2023) and Greenland halibut (Bassi et al. 2023). The unsupervised clustering method employs a multitude of decision trees to distinguish the original dataset from a synthetic dataset generated through bootstrapping of individual variables. A proximity matrix, representing the frequency with which individuals co-occur in terminal nodes of the trees, is transformed into a dissimilarity matrix. This dissimilarity matrix is subsequently analyzed using partitioning around medoid (PAM) clustering to delineate clusters of halibut based on their core element signatures (Kaufman and Rousseeuw 1990). The appropriate number of clusters was determined using the NbClust R package with Euclidean distances (Charrad et al. 2014), allowing the evaluation of multiple clustering schemes and the identification of the most suitable number of clusters based on 30 different indices.

Once all cores were assigned to a cluster, interpreted as sources, we used principal component analysis (PCA) to visualize the contribution of each element to the different sources. Differences in element concentrations were assessed for each individual element using Analysis of variance (ANOVA) and the Kruskal–Wallis test (nonparametric alternative). Multivariate differences, considering all three elements together, were evaluated using multivariate ANOVA (MANOVA) or permutational multivariate ANOVA (PERMANOVA) as a nonparametric alternative.

Natal origins per cohorts

To study natal origin, we selected cores from all cohorts with a sample size greater than 14 (Table 2). Four cohorts met this criterion: 2006, 2007, 2009, and 2010. To account for potential temporal variation, the cohorts were analyzed independently. The NbClust R package was used to determine

Table 2. Number of Atlantic halibut (*Hippoglossus hippoglossus*) from each cohort.

Birth year	N	Birth year	N	Birth year	N
1998	1	2004	10	2010	14
1999	1	2005	12	2011	9
2000	2	2006	15	2012	6
2001	3	2007	24	2013	6
2002	12	2008	13	2014	1
2003	13	2009	21	2015	1

Note: Cohorts selected for further analysis are marked in bold.

the optimal number of sources and unsupervised RF methods allowed for data division without prior classification knowledge. PCA was applied to each cohort to visualize which elements contributed most to the differences among sources. To assess whether the chemical signatures varied significantly among sources, both ANOVA and MANOVA were conducted.

Migration contingent and their natal origins

Based on whole-transect chemistry results from Gauthier et al. (2024), each halibut in our sample was classified as a resident, annual migrant or irregular migrant. Using individuals from the 2006, 2007, 2009 and 2010 cohorts, we estimated the proportion of every migratory contingent coming from each source. Fisher's exact test was used to evaluate the association between the migration contingent and source assignment, as it is a nonparametric test suitable for small sample sizes.

Results

Spatial and temporal variations in all core fingerprints

The optimal number of sources based on the core fingerprints was three. The first principal component (PC1) of the PCA was primarily influenced by a positive relationship between Sr and Ba, while Mg drove the second principal component (PC2) (Fig. 2). Source 1 exhibited the highest concentrations of Sr and Ba, while Source 3 was characterized by lower Mg levels. Sources 1, 2 and 3 regrouped 74, 84 and 35 individuals, respectively. The proportion of contribution of source to each sector of the GSL was similar (Fig. 3). The contribution of each source when dividing the data by birth years for aged individuals was also relatively constant through the years (Fig. S1). Sources 1 and 2 were the main contributors to every sector. Source 3 did not contribute to the sector western of Anticosti Island nor to the southern part of the GSL.

Core analysis per cohort

For all cohorts, the optimal number of sources was three. The contribution of each source showed more spatial structure by cohorts than when looking at all cores (Figs. 3 and 4A). In 2006, source 3 was higher in Sr and Ba than both other sources. In 2007, source 1 was lower in Mg and source 3 was higher in Ba. In 2009, source 3 was higher in Mg and

the three sources had different concentrations of Ba, source 1 having the lowest and source 2 the highest. No significant differences among sources were found in 2010 (Fig. 4B). The main drivers of each source for each cohort can also be visualized by PCA in Fig. S2. Multivariate analysis of PERMANOVA showed significant differences between the fingerprints of the three sources for 2006 ($F_{[2,13]} = 8.0716$; $P = 0.003$), 2007 ($F_{[2,21]} = 11.445$; $P < 0.001$), 2009 ($F_{[2,18]} = 4.4107$; $P = 0.017$) but not for 2010 ($F_{[2,12]} = 1.9312$; $P > 0.05$).

Origins per migration contingent

There were no clear patterns between migration contingent and sources (Fig. 5). Fisher's Exact Test for each cohort (2006, 2007, 2009, and 2010) showed no significant association between migration contingent and source assignment (two-tailed $P > 0.05$).

Discussion

In this study, we used otolith core elemental fingerprints to estimate the number of natal sources contributing to the halibut stock in the GSL and to quantify their relative importance. Our results suggest the presence of three sources, each contributing in similar proportions across most of the GSL, indicating a high degree of mixing. We also re-examined individuals' migratory histories in relation to these natal origins and found no significant association between origin and subsequent migratory strategy. These findings complement previous work that examined movement patterns across ontogeny using full otolith transects (Gauthier et al. 2024) to provide a broader understanding of spatial structuring throughout ontogeny.

Quantify natal origins

It is particularly difficult to study early life stages of Atlantic halibut in the GSL considering that they do not appear in summer surveys before reaching a size of 30 cm. Since halibut reproduction is thought to happen in winter with a peak in February (Gatti et al. 2020), winter sampling could offer more opportunities to capture young halibut, but it poses a lot of challenges. A recent winter survey targeting Atlantic halibut larvae only captured eight individuals, confirming local reproduction despite low catch (Ghinter et al. 2023). PSATs studies regrouped their observations of potential spawning behaviour into four zones, with two of them being close to the mouth of the Laurentian channel (Gatti et al. 2020; Shackell et al. 2021). Two areas spatially closer to each other might not be chemically contrasted enough to translate into different chemical fingerprints and could be regrouped as one source in our results.

Spatial variability in core fingerprints

With analyses by cohort, we observed significant differences in the chemistry of the three sources (except for 2010), suggesting that the individuals coming from different sources would have experienced different water conditions during approximately the first 6 months of their lives.

Fig. 2. Principal component analysis (PCA) of Mg, Sr, and Ba concentrations in the cores of Atlantic halibut (*Hippoglossus hippoglossus*) from all samples. The direction of the arrows indicates the relative contributions of each element to the principal components. Sources, determined through unsupervised random forests and interpreted as representing different origins, are shown in distinct colors.

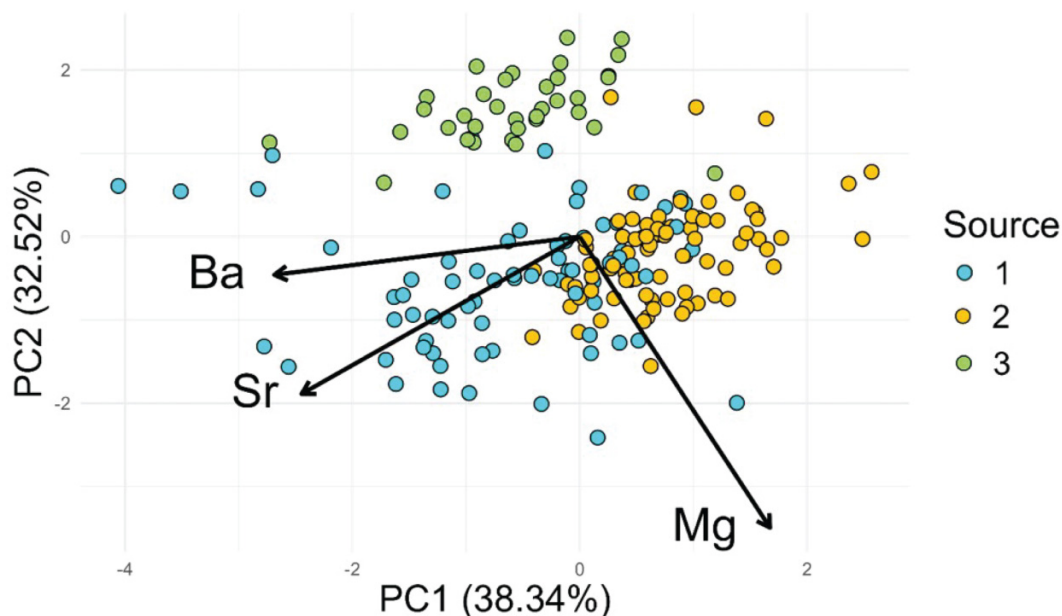


Fig. 3. Pie charts of the contribution of each source to capture sectors. All Atlantic halibut (*Hippoglossus hippoglossus*) with birth years ranging from 1998 to 2015 are included ($N = 187$). The size of the pie chart is proportional to the effective (N). Isobaths come from the NONNA database, Canadian Hydrographic Service, Fisheries and Oceans Canada 2023; map is in NAD83/Statistics Canada Lambert projection, EPSG:3347.

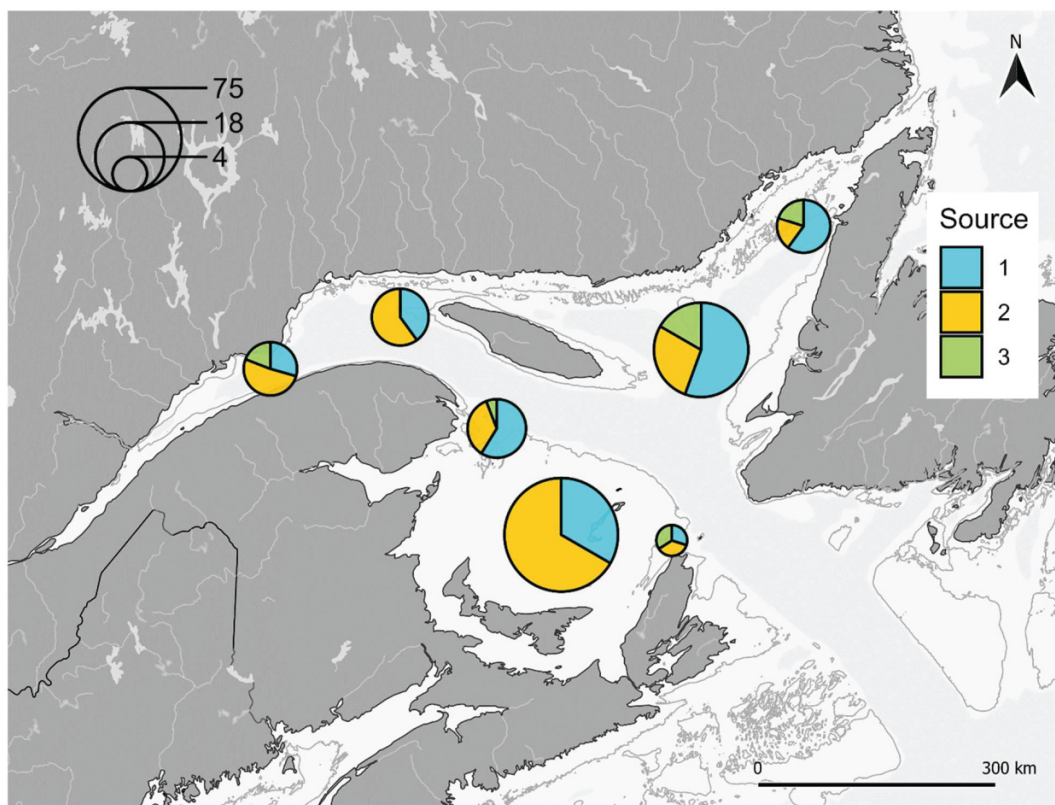
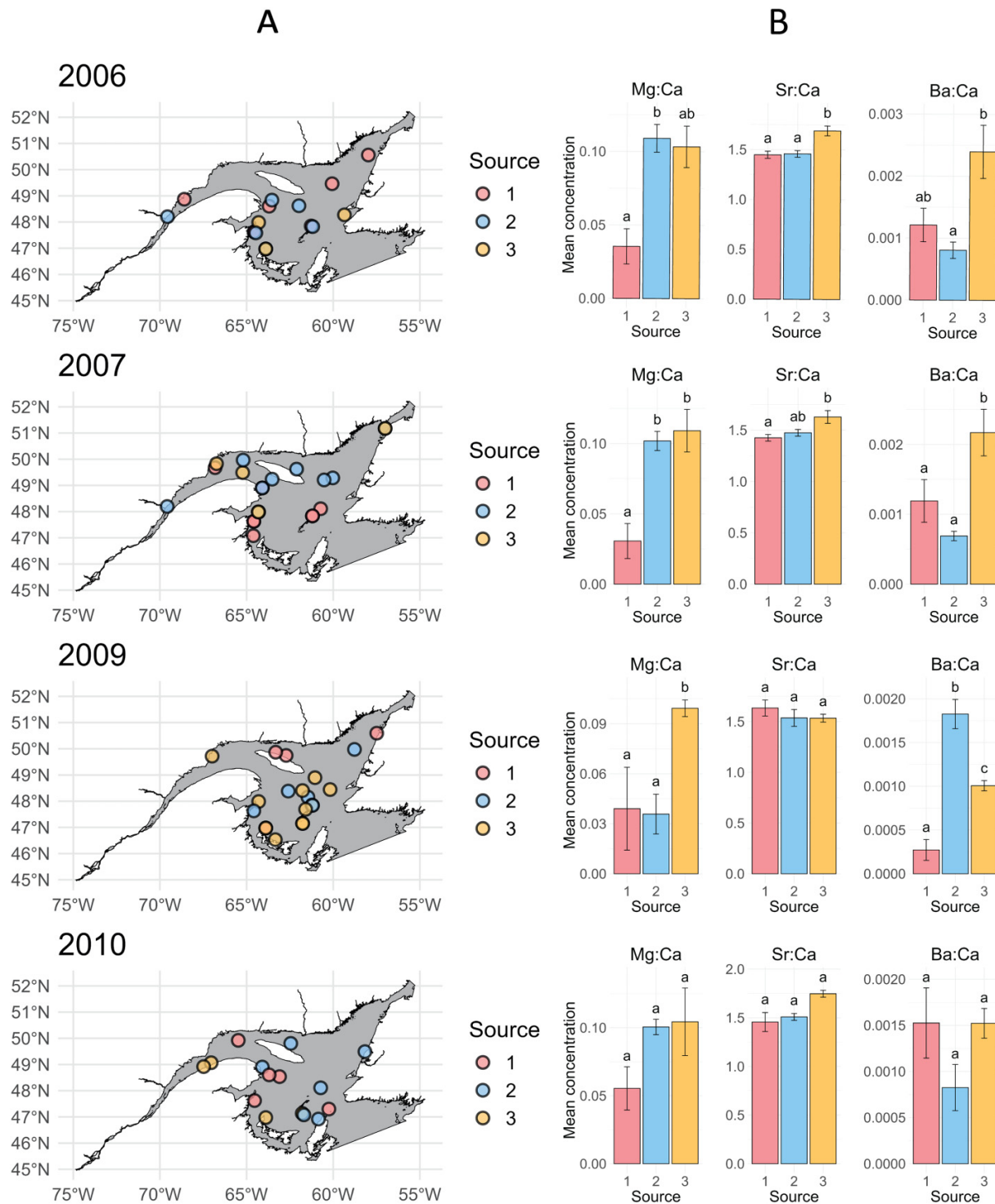


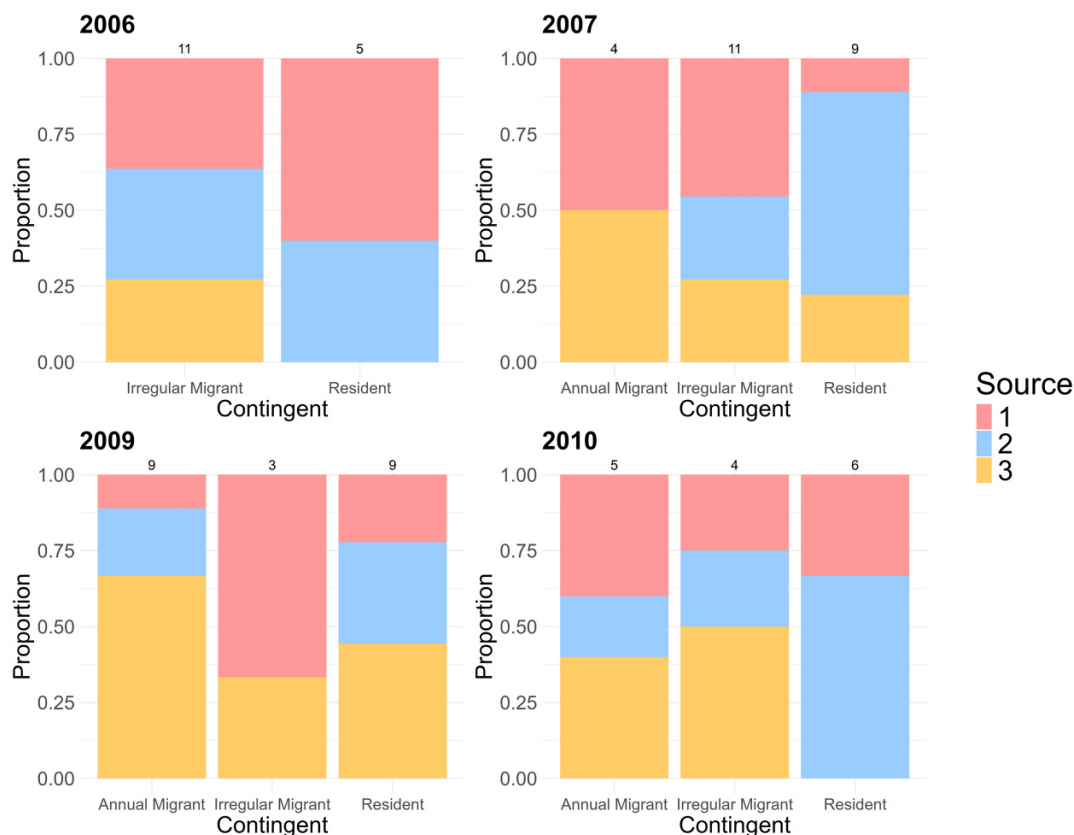
Fig. 4. Spatial distribution (A) and concentrations of Mg, Sr, and Ba (B) of each source of Atlantic halibut (*Hippoglossus hippoglossus*) per cohort (2006, 2007, 2009 and 2010). Sources were determined separately for each cohort using unsupervised random forests. (B) Significant differences between sources are marked by different letters. Gulf of St. Lawrence boundary based on the International Hydrographic Organization limits (Marine Regions 2023). Map is shown in WGS84 geographic coordinates (EPSG:4326).



Using the otolith's edges, Gauthier et al. (2024) differentiated between shallow and deep water, but did not find an evident 2D pattern. Since all reproduction events are hypothesized to happen at a similar depth and that the greatest con-

trast in chemistry that was observed with edges was based on depth (Gauthier et al. 2024), we expected lower chemical difference with the core signatures. Other otolith chemistry studies from the GSL showed a gradient of Sr and Ba, getting

Fig. 5. Proportions of each source’s contribution to the contingents for the 2006, 2007, 2009, and 2010 cohorts of Atlantic halibut (*Hippoglossus hippoglossus*), with effective (*N*) values shown above the columns. Sources were determined separately for each cohort using unsupervised random forests.



stronger towards the eastern part of the GSL (Bassi et al. 2023; Coussau et al. 2023). Some interannual differences have been observed, so comparisons between years must be taken carefully (Coussau et al. 2023). Bassi et al. (2023) also used Mg as a marker that was higher in the western part of the GSL. Based on this knowledge, we can hypothesise that the source that shows higher concentrations of Sr and Ba (mainly source 3), would be the most eastern one, while the source with the lowest Mg concentration (mainly source 1) could be around the western part of the GSL.

In March, at the end of the reproduction period for halibut, surface water temperatures (0–75 m) in the eastern GSL are below 0 °C. Temperatures suitable for Atlantic halibut larval survival (>4.0 °C; Pittman et al. 1989) are restricted to depths greater than 200 m (Galbraith et al. 2024). Marshall et al. (2023) observed that the top of spawning rises occurred at an average depth of ~250 m. North of the Gaspé Peninsula, eggs deposited at depths over 200 m experience temperatures of 4.5–5.5 °C, varying by location. In comparison, deeper waters in the Cabot Strait are warmer, with temperatures ranging from 5.5 to 6.5 °C (Galbraith et al. 2024). These differences in temperature could explain some of the chemical differences between core fingerprints. Indeed, temperature could affect the incorporation of Sr and Ba, either making it higher (Reis-Santos et al. 2013; Coussau et al. 2023) or lower (Elsdon and Gillanders 2002; Gretchen Bath and Mark 2006). Mg can also

be affected positively by temperature (Barnes and Gillanders 2013).

As spring progresses, GSL surface waters warm, sea ice melts, and continental runoff creates a warm surface layer. Below this layer, cold waters from the previous winter become isolated, forming a cold intermediate layer. This layer, located between 50 and 100 m, has temperatures between 0 and 1 °C, while the surface layer (<50 m) warms to around 6 °C (Galbraith et al. 2024). To access the warmer surface waters optimal for feeding and growth, larvae must cross the cold intermediate layer; however, the timing of this vertical migration remains uncertain. Variations in the timing of this migration could influence core fingerprints, as the vertical separation of water masses contributes to distinct edge fingerprints (Gauthier et al. 2024). It is important to note that, given that spawning is thought to occur between December and April (Marshall et al. 2023), the birth month may have a slight effect on otolith chemistry. However, we consider this effect negligible compared to spatial contrast in water chemistry.

Mixing and connectivity

The contribution of each source to the stock did not exhibit a clear spatial pattern. When analyzing all cores together, sources 1 and 2 were the primary contributors. Source 3, with lower Mg concentrations, did not contribute to the zone near

the western end of Anticosti Island but was more prominent in the Estuary, suggesting that this source may still be present throughout the GSL. When analyzed by cohorts, the source with lower Mg concentrations did not seem to have a smaller contribution to the stock. Individuals from the same source were more spatially grouped, but they were not necessarily exclusive to any particular area of the GSL. This could indicate that currents transport individuals from the same source to shared nursery areas. Adult Atlantic halibut exhibit summer site fidelity (Le Bris et al. 2018; Gatti et al. 2020) and recurring migration patterns throughout their lives (Gauthier et al. 2024), suggesting that halibut from the same nursery area could remain spatially close. Halibut have also shown extensive migrations throughout the GSL (Gatti et al. 2020). Dispersion in juvenile or adult stages could partially explain the lack of clearly defined spatial groups from the same natal origin. Fish originating from the source with higher Sr and Ba, typically source 3, did not always group together in the same area. The contribution of sources to different areas may vary across years due to shifts in larval dispersion, driven by changes in currents or physico-chemical conditions. Overall, the contribution of all natal sources to the GSL suggests a high degree of mixing at the stock scale. This aligns with genetic studies, which indicated an absence of differentiation within the GSL Atlantic halibut stock (Kess et al. 2021).

Linking natal origins with migrations strategies

Our results showed no clear link between natal origin and migration behaviour. One potential explanation for the observed differences in migration behaviour could lie in variability in environmental factors experienced during early life. Partial migration, where only a part of the population participate into migration, is often explained by the “threshold model” which suggests that individuals adopt specific migratory behaviours based on whether they reach a certain size or energetic state early in life (Brodersen et al. 2008; Pulido 2011). This can be viewed as a carryover effect, where early-life environmental conditions, such as temperature and food availability, directly affect individual growth and energy reserves. Growth differences early in life can also be attributed to factors such as timing of spawning, social hierarchy, feeding strategies, population density, and sex-specific traits (Jonsson and Jonsson 1993; Secor 1999). Since halibut spawning is thought to happen in deep channels of the GSL, which share relatively uniform conditions, it is possible that these areas do not offer sufficient environmental variations to trigger the threshold required for partial migration.

Conclusion

While our findings align with existing knowledge of halibut in the GSL and suggest that the origins could likely be grouped into three sources experiencing similar environmental conditions, it is important to acknowledge potential limitations. The heterogeneous contribution of each source across all zones in the GSL might also reflect a chemical signal too weak to capture spatial differentiation accurately. The sample sizes per cohort are small, which could limit our ability to generalize our findings at the stock scale. Additionally,

the lack of access to otoliths from young halibut constrains our ability to draw definitive conclusions. To address this, a larger sample size from a single cohort, to improve chemical resolution, would be necessary. Our results remain plausible and consistent with ecological expectations, offering first insights into Atlantic halibut early life dynamic and providing a solid foundation for future studies.

Otolith chemistry holds significant potential as a method for studying the early life history of fish, particularly in situations where capturing large numbers of young individuals is challenging, as it is for Atlantic halibut. Targeted sampling of specific cohorts could provide more accurate estimates of each source’s contribution to the overall stock. Given the rapid and steady rise in water temperatures in the GSL, it is crucial to monitor the sources and their contribution, as continued warming may alter reproduction timing, potentially affecting larval survival and recruitment to the fishery—even if, for now, rising temperatures in Canadian waters are associated with improved habitat conditions (Czich et al. 2023).

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Data availability

Data analyzed during this study are available from the corresponding author upon reasonable request. This research was conducted as part of a doctoral thesis, which is available

at the following link: <https://constellation.uqac.ca/id/eprint/10155/>.

Author information

Author ORCIDiDs

Charlotte Gauthier <https://orcid.org/0009-0006-2602-941X>

Pascal Sirois <https://orcid.org/0000-0003-1272-5730>

Author contributions

Conceptualization: CG, PS

Data curation: CG

Formal analysis: CG

Funding acquisition: JADF, DR, PS

Investigation: CG

Methodology: CG

Project administration: JADF, DR, PS

Software: CG

Supervision: JADF, DR, PS

Validation: CG, PS

Visualization: CG

Writing – original draft: CG

Writing – review & editing: CG, JADF, DR, PS

Competing interests

The authors declare there are no competing interests.

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Supplementary material

Supplementary data are available with the article at <https://doi.org/10.1139/cjz-2025-0049>.

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