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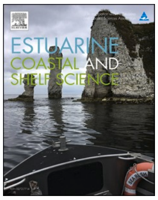

Unraveling habitat use and movement patterns of *Pogonias courbina* in Southwest Atlantic lagoon systems using otolith microchemistry

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ABSTRACT

Black drum, *Pogonias courbina*, is an important but overexploited fishery resource in southeastern Brazil lagoon systems with a vulnerable status on the IUCN Red List of Threatened Species. To improve understanding of *P. courbina* life history and fishery sustainability, otolith microchemistry was used to characterize habitat use in two Brazilian lagoon systems in the southwest Atlantic (Saquarema-RJ and Araruama-RJ). Following age estimation from annual growth increments, otolith core-to-edge Sr/Ca, Ba/Ca and Mn/Ca signatures for forty (40), 2-year-old, individuals (20 per site), collected between November 2019 and April 2020, were measured by laser ablation inductively coupled to plasma mass spectrometer (LA-ICP-MS) to document ontogenetic chemical variations. Spearman correlation, Generalized Addictive Models (GAMs) and Change point analysis were used to assess habitat-use patterns among the study individuals. Two habitat-use patterns for *P. courbina* were identified consistent with estuaries with a well-defined salinity gradient: (i) movements in mesohaline waters with low salinity, and (ii) movements in polyhaline waters with intermediate salinity. These findings confirm that *P. courbina* is estuarine-dependent, likely utilizing different salinity environments as nurseries. The species shows high habitat-use plasticity. Ba/Ca and Sr/Ca fluctuations track distinct movement patterns (profiles), while Mn/Ca peaks reflect rapid somatic growth during the larval-juvenile transition, making these otolith chemical markers effective tracers of *P. courbina* life history.

1. Introduction

Coastal lagoons play a crucial role in the export of nutrients, detritus, and fish biomass to coastal areas (Friedman, 2011; Ramos et al., 2016; Almeida et al., 2023). Various fishes contribute to this dynamic, moving in response to feeding, shelter, and reproductive needs at both the population and individual levels (Nagelkerken, 2009; Ramos et al., 2014; Pelage et al., 2021).

The connectivity among coastal waters, nearby estuaries and coastal lagoons, and spawning grounds areas is vital for defining habitat use by fish, including crucial nursery areas during vulnerable early life stages. Estuaries, in particular, serve as critical development areas, supporting fish from juvenile stages until adulthood and facilitating their dispersal (Dantas and Barletta, 2016; Camara et al., 2020; Almeida et al., 2023). This connectivity underscores the importance of these complex habitats in maintaining adult fish stocks in both coastal and estuarine fishing zones (Herbst and Hanazaki, 2014; Avigliano et al., 2017; Ferreira et al., 2023).

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Most species in the Sciaenidae family undergo ontogenetic migrations, utilizing a variety of habitats such as beaches, mangroves, estuaries, coastal lagoons, and bays. As juveniles, they inhabit shallow waters within these environments, and as they mature, they migrate to offshore habitats like the continental shelf. There, they establish different types of aggregations, including schools, spawning groups, or feeding assemblages (Militelli et al., 2013; Odell et al., 2017; Franco et al., 2023).

The behavioral traits of species within this family align with the descriptions and classifications of biological communities, based on taxonomic similarities, size and biomass spectrum of individuals, and observable functional attributes (Potter et al., 2015). Integrating this information with well-documented properties of estuaries—such as migration routes, refuge areas, feeding, and reproduction (Elliott et al., 2007; Olsen et al., 2018; Franco et al., 2019), reinforces understanding that these species are obligatory users of estuarine areas. Recognition that several commercially important fish species utilize these environments at some stage of their life cycles reiterates their classification as estuary-dependent species (Franco et al., 2019; Franzen et al., 2019; Almeida et al., 2024a).

Otolith microchemical analysis has emerged as a crucial tool for characterizing fish habitat use patterns, enabling the tracking of their movements and identifying origin areas. This utility arises because uptake of some elements during otolith growth occurs in proportion to those in ambient water, thus otoliths constitute a natural marker of experienced habitats (Avigliano et al., 2015b; Santana et al., 2018; Almeida et al., 2024b). Accordingly, many researchers have applied advanced analytical techniques, such as laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS), to quantify minor and trace elements along the growth axis of otoliths, from core to edge, to reconstruct migratory patterns and environmental history of fish through life (Vignon, 2015; Corrêa et al., 2022; Ferreira et al., 2023). On the coast of southeastern Brazil, several studies have used this approach, with Sr/Ca and Ba/Ca being the elemental ratios most applied as indicators of with water masses of different salinities, whereas Mn/Ca is commonly employed as a proxy for terrigenous input and hypoxic conditions in estuarine environments (Avigliano et al., 2017; Soeth et al., 2020; Lopes et al., 2023).

The black drum, *Pogonias courbina* (Lacepède, 1803), is classified as endangered in Brazil primarily due to overexploitation (Brasil, 2014). *Pogonias courbina* was recently discriminated from *Pogonias cromis*, which occurred in the western Atlantic and is now restricted to the northwestern Atlantic (Azpelicueta et al., 2019). *Pogonias courbina* is found along the southwestern Atlantic Ocean, from the State of Rio de Janeiro (Brazil) to the southern Gulf of San Matias (Argentina), inhabiting coastal marine areas and estuarine ecosystems (Azpelicueta et al., 2019; Almeida et al., 2021; Santos and Velasco, 2021). Estuarine environments host juveniles year-round, whereas adults are more common during reproductive periods, suggesting that estuarine ecosystems may serve as spawning and recruitment areas (Blasina et al., 2010; Santos et al., 2016; Haimovici and Cardoso, 2017). Legal, illegal and non-compliant fishery practices targeting black drum in southern Brazil, including use of illegal fishing gear and fishing during off-season periods, have contributed to stock collapse and continue to hinder population recovery (Velasco et al., 2007; Chao et al., 2015; Haimovici and Cardoso, 2017). A monitoring program (Eastern Rio de Janeiro Lagoon Systems Project) in southeastern Brazil reported catches of 1.4 tons in Saquarema Lagoon between autumn and winter 2020, while the Araruama Lagoon system reported 389 tons captured between 2019 and 2020, identifying the specie as an important fisheries resource (Tubino et al., 2021).

The Saquarema and Araruama lagoon systems contribute with numerous ecosystem services and provide habitats for species of high socioeconomic importance, including *P. courbina*. These lagoons are located at the northern limit of the distribution of *P. courbina*, and also have very different environmental conditions, raising questions about the behavior of the species in different scenarios. The movement patterns and habitat use of *P. courbina* in Saquarema and Araruama lagoon systems is unknow. Understanding the life history traits of the specie in these ecosystems is essential for developing effective management strategies for this economically important and threatened species. Here, otolith core-to-edge analysis was applied to reconstruct movement patterns and habitat use of *P. courbina* within these ecosystems.

2. Material and methods

2.1. Study area setting

Specimens of *Pogonias courbina* were collected from Saquarema (SQ) and Araruama (AR) lagoon systems in eastern Rio de Janeiro state, Brazil, both of which exhibit salinity variations typical of estuarine environments (Miranda et al., 2012). Salinity decreases landward from the coastal marine zone to the lagoon's interior in both Lagoons, but Araruama (10x larger, 9x deeper) receives significant freshwater input from numerous tributaries draining into the lagoon interior toward the intermediate zone (Fig. 1; Table 1). The climate in the study region ranges from humid in the west to semi-arid in the east, with tidal (mesotidal) and salinity variations sensitive to small- and large-scale weather events, river runoff, and hydraulic gradient intensity (Barbieri and Coe-Neto, 1999; Mansur et al., 2012; Miranda et al., 2012). These factors control temporal and spatial variations in freshwater-to-marine salinity gradients in both lagoon systems.

2.2. Fish sampling and otoliths processing

A total of 402 individuals from the SQ (N: 145) and AR (N: 257) lagoons were obtained directly from artisanal fishermen between July 2019 and April 2020. Due to the greater abundance in both lagoon systems in a restricted period of time (6 months: November 2019 and April 2020), age-2^+ individuals – the most abundant age class – were randomly selected for comparative analyses between SQ (N: 20) and AR (N: 20). SQ fish were captured in the innermost part of the lagoon system (Mombaça Lagoon), whereas AR fish were collected at Baleia Beach, an important fish landing port. Main AR fishing grounds extend AR from Ponta da Alcaíra, Massambaba, Ponta do Sudoeste, and Iguaba Grande inlet (dotted ellipse in Fig. 1). Twenty (20) *P. courbina* specimens from each lagoon system (SQ TL: 31.2 ± 0.9 cm; AR TL: 30.4 ± 0.05 cm) were selected for the present study and stored in ice during transportation (Table 2). In the lab, sagittal otoliths were extracted with plastic tweezers, washed with distilled water to remove organic tissues and stored dry in plastic tubes. Otolith pairs (left and right *sagittae*) were distinguished according to the position of the *rostrum* and *sulcus acusticus* (Secor et al., 1992).

For age determination and microchemical analysis, left otoliths were embedded in clear epoxy resin (Buehler, Epothin), then sectioned transversely with a precision low-speed diamond saw (Buehler, Isomet), to obtain 0.6 mm-thick slices intersecting the core region. The obtained transverse sections were mounted to slides using crystal bond and then ground using silicon abrasive papers of varying grit sizes (800, 1200, and 2400; Buehler, Ø 200 mm SiC Paper) to reveal the core, then polished using 6, 3, and 1 μm diamond pastes (Buehler, Metadi II) (Correia et al., 2012) to provide transparent otoliths with smooth flat surfaces. Otolith slices, immersed in glycerol, were examined under magnification (Leica S9i stereoscopic microscope,6× magnification) to visualize annual growth increments (annuli) for age estimation. Only otoliths from adults with ages corresponding to the 2^+ age group (A_{50}: 2 years) (Olsen et al., 2018; Santos and Velasco, 2021), as determined independently by two experienced readers (Almeida et al., 2024a), were selected for analysis.

Elemental concentrations were determined using an Elemental Scientific NWR193UC (193 nm wavelength, <4 ns pulse width) laser system, coupled to an Agilent 7500ce inductively coupled mass

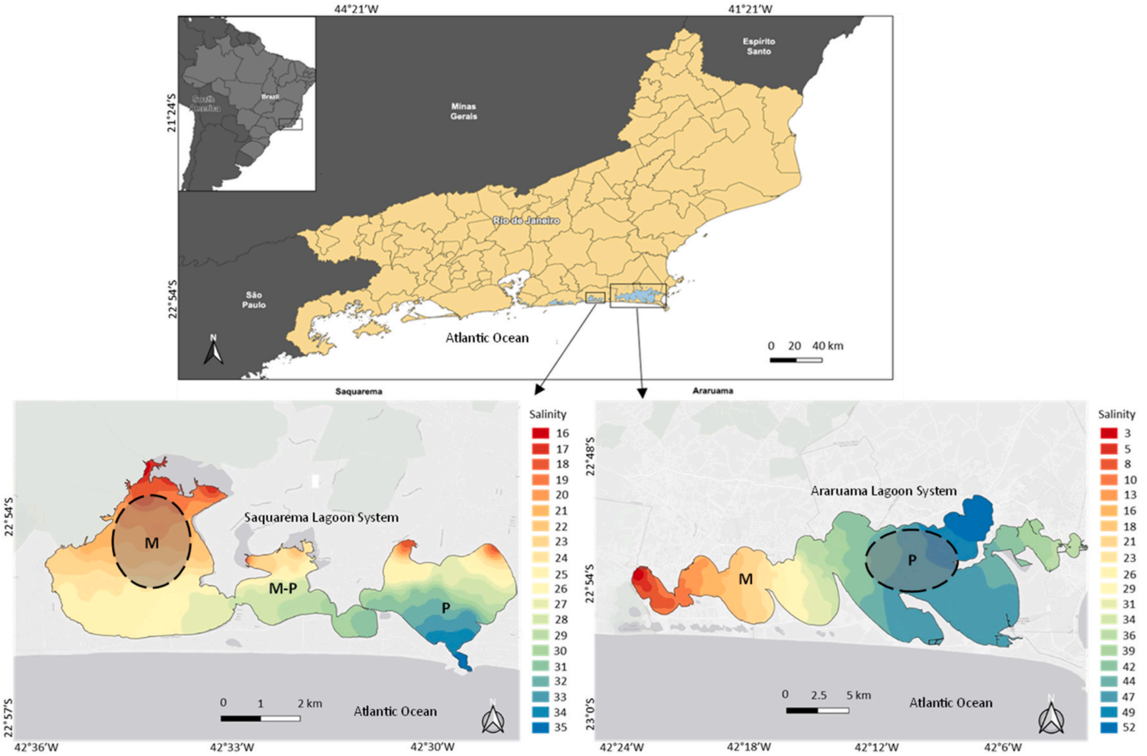

Fig. 1. Maps of the southeastern coast of Brazil, Rio de Janeiro (A), highlighting Saquarema (B) and Araruama (C) lagoon systems of the Eastern Fluminense region, RJ, showing mesohaline (M), polyhaline (P) and transitional (M–P) salinity regions (adapted from SisBaHiA® 2024) and fishery capture regions (dotted fields).

Table 1
Location, hydrological parameters, trophic state and anthropogenic influences for Saquarema and Araruama lagoon systems, eastern Rio de Janeiro, Brazil.

Lagoon System	Coords.	Area (km^2)	Drainage basin (km^2)	Depth range (m)	Water residence time (days)	Water Temp (°C)	Salinity (‰)	Average rainfall (mm/yr)	Type and Trophic state	Predominant anthropogenic contributions
Saquarema Subsaline: Positive FW balance (ppn + river discharge – evap >0).	22°93′S 42°49′W	21.2	215	0.6–2.4	27	18–33	9–34 < coastal region	1.3	Suffocated Lagoon supereutrophic	Domestic sewage/ agricultural waste
Araruama Hypersaline: Negative FW balance (ppn + river discharge – evap <0).	22°88′S 42°01′W	225	285	0.5–18	84	21–29	12–60 > coastal region	0.9	Suffocated Lagoon supereutrophic	Cultural eutrophication/ intense tourism/mineral extraction: salt and shell limestone

Table 2
Sample size (N) and total length (TL) of *Pogonias courbina* individuals collected in the two lagoon systems of eastern Rio de Janeiro, Brazil. Values are presented as means, standard errors (SE) and ranges.

Lagoon System	N	TL (cm)		
		Date of collection	Mean ± SE	Range
Saquarema (SQ)	6	Nov. 2019	31.4 ± 1.2	19.9–39.0
	1	Jan. 2020		
	1	Feb. 2020		
	11	Mar. 2020		
	1	Apr. 2020		
Araruama (AR)	2	Dec. 2019	30.7 ± 0.5	26.4–34.4
	6	Jan. 2020		
	9	Feb. 2020		
	3	Mar. 2020		

spectrometer. The laser system was equipped with a large format two-volume laser cell with fast washout (<1s), which accommodated all otolith samples and standards in two separate loadings. Laser ablation parameters were optimized for sensitivity and signal stability from test ablation transects on representative unknowns (Table 3). Prior to analysis, samples and standards were pre-ablated to remove potential surface contamination. Laser analyses of unknowns were bracketed hourly by standard measurements (MACS-3 and NIST 612, typically measured in triplicate for 60-s).

To characterize ontogenetic movement patterns, otoliths were

Table 3
Spearman correlations among otolith element/Ca ratios of *Pogonias courbina* by lagoon system and age group. *p < 0.01; **p < 0.001; ***p < 0.0001.

Element/Ca	SQ		AR	
	Age 1	Age 2	Age 1	Age 2
Sr/Ca vs Ba/Ca	0.20***	0.17***	0.44***	0.35***
Sr/Ca vs Mn/Ca	0.16***	0.01	−0.01*	−0.05***
Mn/Ca vs Ba/Ca	−0.05***	0.15***	−0.10***	−0.10***

continuously ablated in core-to-edge transects, using a 35 μm spot at a scan rate of 10 μm/s. The quadrupole time-resolved method measured 7 masses using integration times of 10 ms ($^{43\text{-}44}$Ca, ^{88}Sr), 20 ms (^{55}Mn), and 50 ms (^{137}Ba). The sampling period of 0.4032 s corresponds to 94.25 % quadrupole measurement time. The scan rates of 10 μm/s respectively correspond to analyte measurements every 4.032 μm along transects. Time-resolved intensities were converted to concentration (ppm) equivalents using Iolite software (Hellstrom et al., 2008), with ^{43}Ca set as the internal standard and a Ca index value of 38.3 wt %. Baselines were determined from gas blank intervals (35 or 60 s), measured while the laser was off and all masses were scanned by the quadrupole. USGS MACS-3 was used as the primary reference standard and accuracy and precision were proxied from replicates of NIST 612 analyzed as an unknown. Average analyte recovery factors for all runs of NIST 612 were 0.98 ± 0.05 (N = 64) relative to GeoREM preferred values (http://georem.mpch-mainz.gwdg.de). The raw data (counts/s) in ppm were converted to elemental concentration rationed to calcium (element/Ca) and presented as molar ratios, expressed as mmol/mol for Sr/Ca and μmol/mol for Mn/Ca and Ba/Ca.

2.3. Data analyses

Otolith transect distances were measured for age group 1 (from the core to the first annulus) and age group 2^+ (from the first annulus, through the second annulus, to the otolith edge) to evaluate whether age-specific distances were comparable between lagoon systems (Soeth et al., 2020). Differences between average element/Ca ratios by age group and location were evaluated using a bifactorial PERMANOVA (Soeth et al., 2020). Then bifactorial PERANOVAS were also performed for each element separately. The results are presented as mean ± standard errors. Correlations among otolith element/Ca ratios across lagoon systems and age groups were assessed using Spearman correlation coeficient (Fowler et al., 2016; Avigliano et al., 2017; Soeth et al., 2020). The univariate and multivariate analysis were executed in the vegan (Oksanen et al., 2021) and exchange packages in the R programming environment (R Development Core Team, 2025). A significance level of $p < 0.05$ was assumed.

Sr/Ca, Ba/Ca, and Mn/Ca ratios along the otolith transect, from the core to the edge, were evaluated by lagoon system, age group, and capture date using Generalized Additive Models (GAMs). Models were fitted assuming a Gaussian distribution with an identity link function and thin-plate regression spline smoothers. Ninety-five percent confidence intervals and p-values were estimated using a Bayesian framework (Brennan et al., 2015; Soeth et al., 2020; Ng et al., 2025). The analyses were implemented with the MGCV package in the R programming environment (R Development Core Team, 2025).

The "Identifying Changes in Mean" (ICM) algorithm, from the changepoint R package (Killick and Eckley, 2014), was applied to Sr/Ca, Ba/Ca and Mn/Ca profiles to evaluate significant changes in fish movement patterns. The assumption of a positive correlation between Sr/Ca ratios and gradient salinity was used to evaluate the movement patterns of *P. courbina* across different habitats. Transition thresholds between water masses of varying salinities were estimated based on the last three spot's readings (approximately 12 μm) at the otolith edge—representing the elemental signature of the capture site—of individuals collected in the inner zone of SQ (Tabouret et al., 2010). To assess transitions between lower and higher salinity zones, threshold values were calculated based on Sr/Ca ratios from otolith of black drum caught in the upper estuarine zone of SQ (a typically estuarine brackish ecosystem) to estimate the entry of individuals in the sea water coastal line, using the formula: Mean + 1 × Standard Deviation (adapted from Tabouret et al., 2010; Menezes et al., 2021; Ferreira et al., 2023). Values of Sr/Ca below the calculated threshold (2.64 mmol/mol) were classified as mesohaline waters, while higher values were classified as polyhaline waters. Individuals exhibiting Sr/Ca ratios consistently below the defined threshold along the entire otolith transect, from core to edge, were classified as mesohaline residents (M). In contrast, individuals for which the Sr/Ca ratio exceeded the threshold at least once along the transect were classified as mesohaline–polyhaline (MP). The threshold was applied exclusively to Sr/Ca ratios; however, Ba/Ca and Mn/Ca ratios were used as complementary indicators of water-mass characteristics. The Ba/Ca, Mn/Ca and Sr/Ca profiles with change points and the calculated threshold were plotted together using the R package CPecopesca (Cadilho et al., 2023; R Development Core Team, 2025).

3. Results

The measurements of the transects from the core to the first and second annuli did not show differences between lagoons (PERMANOVA; pseudo-F = 0.4177; df = 1; $p > 0.05$), and were presented with the following values: from the core to the 1st annulus (mean ± SE) was 1079.11 ± 66.35 μm, and from the core to the 2nd annulus was 1596.46 ± 65.85 μm for SQ. In the case of AR, the measurements were as follows: from the core to the 1st annulus was 1125.65 ± 53.48 μm, and from the core to the 2nd annulus was 1533.73 ± 54.87 μm.

The Ba/Ca, Mn/Ca, and Sr/Ca ratios showed significant differences in the multivariate analyses between lagoon systems and ages (PERMANOVA Bifactorial, pseudo-F = 17.683, df = 3, $p < 0.0001$). In the univariate analyses, only Sr/Ca showed significant differences, with higher mean values in AR than in SQ for both age groups, as well as higher mean values for age group 1 in SQ and for age group 2 in AR. (PERANOVA Bifactorial, pseudo-F = 3.928, df = 1, $p < 0.05$) (Fig. 2).

Sr/Ca and Ba/Ca ratios were positively correlated across lagoon systems and age groups (Spearman correlation, $p < 0.0001$; Table 3). In SQ, Sr/Ca and Mn/Ca ratios were positively correlated for age group 1 ($p < 0.0001$), whereas no significant correlation was observed for age group 2 ($p > 0.05$; Table 3). In AR, Sr/Ca and Mn/Ca ratios exhibited a negative correlation for both age groups ($p < 0.05$; Table 3). Mn/Ca and Ba/Ca ratios were negatively correlated for age group 1 and positively correlated for age group 2 in SQ ($p < 0.0001$; Table 3). In contrast, in AR, Mn/Ca and Ba/Ca ratios showed negative correlations for both age groups ($p < 0.0001$; Table 3).

Sr/Ca, Ba/Ca, and Mn/Ca ratios along the otolith transect, from the core to the edge, differed significantly among lagoon systems, age groups, and capture dates (GAM, $p < 0.0001$). When examined by location, Sr/Ca ratios exhibited an increasing trend in AR and a decreasing trend in SQ (Fig. 3A). Ba/Ca ratios showed a relatively stable pattern in AR, whereas elevated values were observed in SQ at approximately 1500 μm along the transect from core to edge (Fig. 3B). Mn/Ca ratios displayed similar patterns in both lagoon systems, with higher values concentrated between 0 and 500 μm from the otolith core (Fig. 3C). When analyzed by capture date, elemental ratios exhibited similar core-to-edge trends between lagoon systems, with differences primarily reflected in concentration magnitudes among sampling periods (Fig. 4A–F). Capture dates with insufficient sample sizes were not plotted for statistical robustness (Fig. 4A–C, and E).

Variations were observed in the Sr/Ca, Ba/Ca and Mn/Ca ratios along otolith core-to-edge transects using the changepoint routine, evidencing similar movement patterns between lagoon systems (Figs. 5 and 6; Supplementary data, Fig. S1–S6). Respective across-transect ranges for Sr/Ca (13.5x), Ba/Ca (91x) and Mn/Ca (5600x) were 0.53–7.16 mmol/mol, 0.79–72.13 μmol/mol and 0.01–55.98 μmol/mol, respectively (Figs. 5 and 6; Supplementary data, Fig. S1–S6). Two movement patterns were identified, based on the concept of a natural estuarine zonation gradient, commonly observed in SQ. Although AR is classified as hypersaline, a similar estuarine zonation pattern was detected from the intermediate zone toward the innermost part of the system, where the largest input of freshwater occurs (Fig. 1). The first movement pattern was restricted to mesohaline waters (innermost zone - M; Relative frequency-overall: 27.5 %; SQ: 90.9 %; AR: 9.1 %) (Fig. 5A–C; Fig. 6A; Table 4). The second movement pattern indicated movements between mesohaline waters, alternating with polyhaline

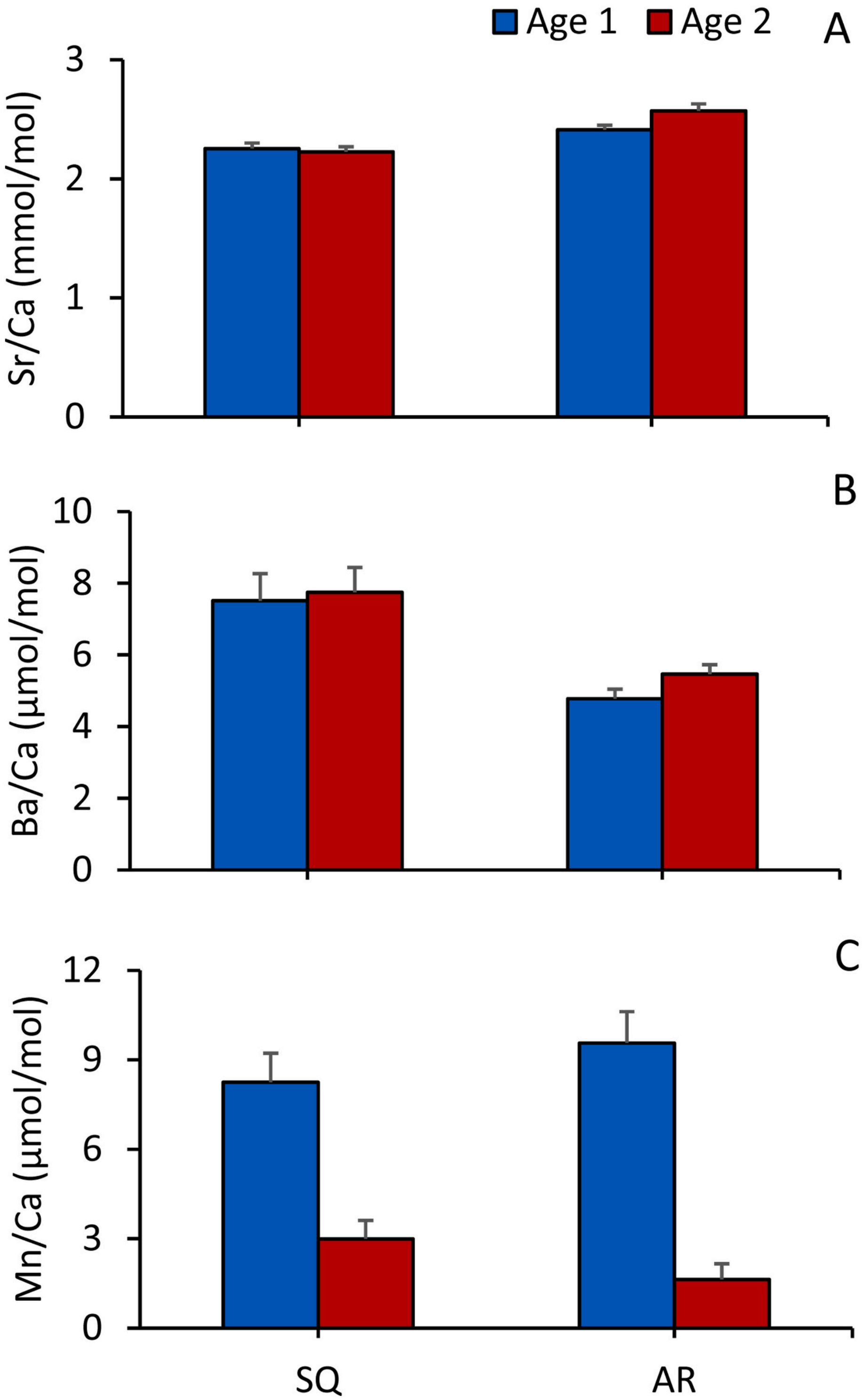

Fig. 2. Means and standard errors of elemental concentrations (Sr/Ca, Ba/Ca, and Mn/Ca) of *Pogonias courbina* otoliths classified by lagoon systems and age group. Age 1: from the core to the first annulus; Age 2: from the first annulus, through the second annulus, to the otolith edge. N = 40 individuals.

waters (from the innermost zones to the intermediate and outer zones - MP; Relative frequency-overall: 72.5 %; SQ: 34.5 %; AR: 65.5 %) (Fig. 5D–F; Fig. 6B–F; Table 4). Because Sr/Ca and Ba/Ca ratios were positively correlated in some AR profiles, Mn/Ca was used as the primary indicator of terrigenous input from continental waters, as it exhibited an inverse correlation with Sr/Ca in this environment (Fig. 6B–D).

4. Discussion

Results of this study reveal variations in elemental profiles of *P. courbina* otoliths between SQ and AR lagoon systems, consistent with heterogeneity in habitat use and movement patterns. Our findings suggest that individuals utilize both lagoon systems primarily as nursery habitats until reaching the age of first sexual maturity (approximately two years). These patterns demonstrate that both environments offer suitable conditions for early development, supporting the idea of high

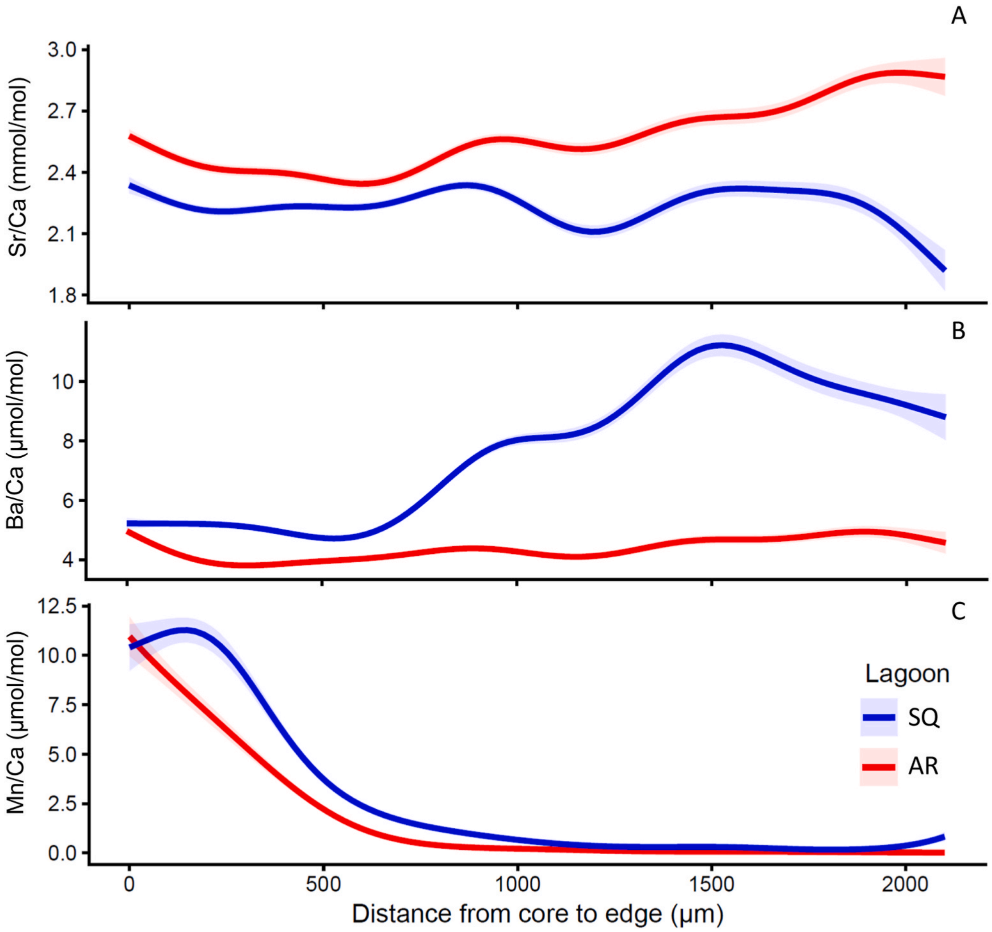

Fig. 3. Fitted Generalized Additive Models (GAMs) and 95 % confidence interval for Sr/Ca (A), Ba/Ca (B) and Mn/Ca (C) elemental ratios in *Pogonias courbina* otoliths, classified by lagoon system (SQ: blue; AR: red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

plasticity in estuarine habitat use by *P. courbina*. Such plasticity may reflect an adaptive strategy to optimize juvenile survival and growth across distinct, yet functionally similar, coastal systems. To better understand the nature of these habitat transitions, we further explored the chemical signatures embedded in the otolith profiles.

The results of the GAMs and Spearman correlation analyses reinforce and refine the interpretation of habitat-use patterns inferred from individual otolith chemical profiles. GAMs revealed consistent ontogenetic trends in Sr/Ca, Ba/Ca, and Mn/Ca ratios along the core-to-edge transect, with marked differences among lagoon systems, age-groups, and capture periods (Figs. 3 and 4).In Araruama Lagoon, the progressive increase in Sr/Ca along the otolith transect (Fig. 3A) indicates increasing exposure to higher-salinity water masses, consistent with the mesohaline–polyhaline movement pattern identified by changepoint analyses (Fig. 5D–F; Fig. 6B–F). In contrast, individuals from Saquarema Lagoon exhibited a declining Sr/Ca trend coupled with Ba/Ca peaks at intermediate otolith regions (Fig. 3A and B), suggesting prolonged residency in inner estuarine environments. This pattern is consistent with the predominantly mesohaline habitat use observed for most individuals in this system (Fig. 5A–C; Fig. 6A). Spearman correlation analyses corroborate these patterns, with positive and negative associations among Sr/Ca, Ba/Ca, and Mn/Ca varying among lagoon systems and ontogenetic stages, reflecting differences in water-mass dynamics and local geochemical processes, as previously described for contrasting estuarine and lagoonal environments (Avigliano et al., 2017; Soeth et al., 2020; Franco et al., 2019).Moreover, elevated Mn/Ca values near the otolith core, well captured by the GAMs (Fig. 3C), support their association with early-life rapid growth and endogenous physiological influences. In contrast, the weakening of Mn/Ca correlations with Sr/Ca at later ontogenetic stages suggests a shift toward stronger environmental control on Sr and Ba incorporation into otoliths (Thomas and Bendell-Young, 1999; Aschenbrenner et al., 2016; Soeth et al., 2020). Taken together, these complementary statistical approaches demonstrate that the smoothed population-level trends identified by GAMs are fully consistent with the individual life-history trajectories revealed by changepoint analyses. This convergence strengthens the interpretation of otolith chemical signatures as reliable archives of habitat-use history in *Pogonias courbina*.

To further interpret this plasticity, we estimated the threshold value between mesohaline and polyhaline waters based on otolith terminal Sr/Ca recorded closest to the time of fish capture for regions of know salinity. This approach has been widely adopted in similar studies to define transitions between water masses in estuarine and lagoonal environments (Fowler et al., 2016; Avigliano et al., 2017; Soeth et al., 2020). Reported Sr/Ca thresholds distinguishing estuarine from marine habitats vary by species—for instance, 6.40 mmol/mol for *Mugil cephalus* (Fowler et al., 2016), 5.98 mmol/mol for *Genidens barbus* (Avigliano et al., 2017), and 3.98 mmol/mol for *Micropogonias furnieri* (Franco et al., 2019). The regional catchment geological composition can also affect the elemental concentrations of endmembers, influencing the salinity-based mixing curve and the variation of salinity thresholds estimated in different geographic locations (Ingram and Weber, 1999; Crook et al., 2016; Höpker et al., 2022). Experimental evidence also supports a positive correlation between Sr/Ca ratios and salinity; for example, *Pogonias cromis* Sr/Ca values of 2.34–3.06 mmol/mol corresponded to salinities of 5–35, respectively (Rooker et al., 2004). Thus,

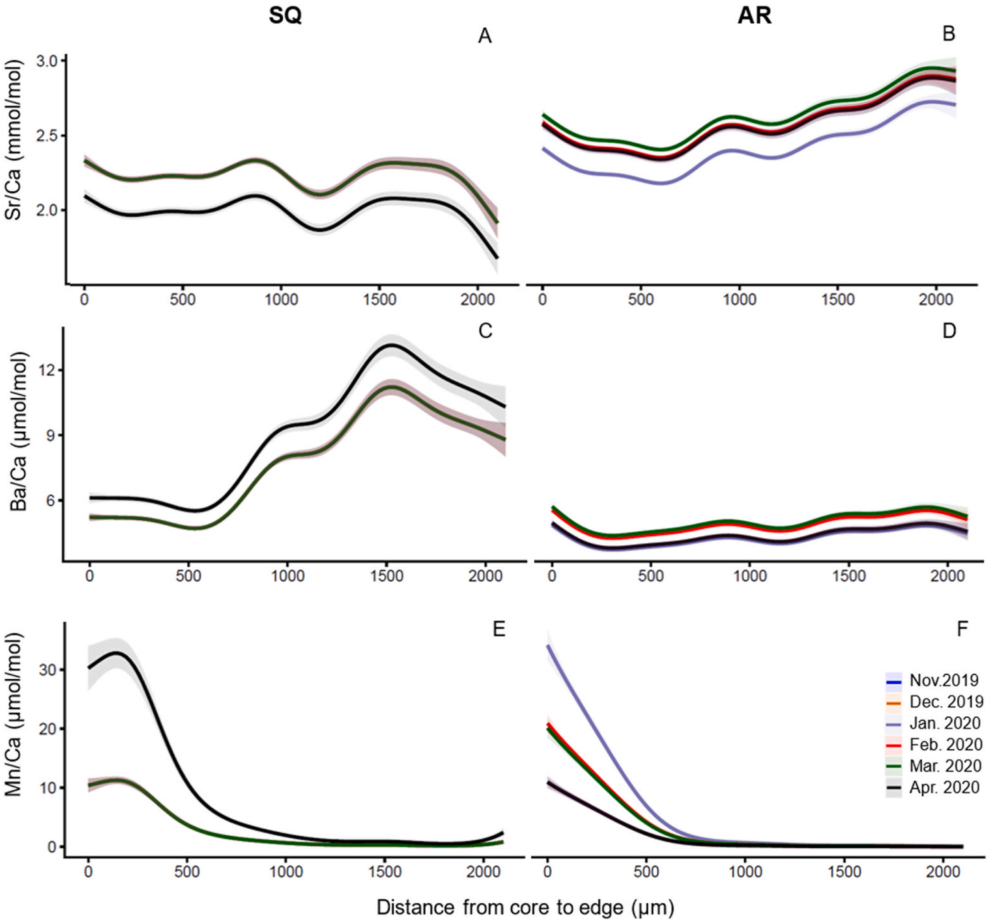

Fig. 4. Fitted Generalized Additive Models (GAMs) and 95 % confidence interval for Sr/Ca (A, B), Ba/Ca (C, D) and Mn/Ca (E, F) elemental ratios of *Pogonias courbina* otoliths, classified by lagoon system and capture date (Nov. 2019: blue; Dec. 2019: orange; Jan. 2020: grey; Feb. 2020: red; Mar. 2020: green; Apr. 2020: black). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

although we did not obtain *in situ* salinity measurements, our Sr/Ca threshold of 2.64 mmol/mol for distinguishing mesohaline from polyhaline waters is consistent with previous experimental and interspecific comparison results. Our results underscore how movements between chemically distinct habitats are reliably recorded in otolith core-to-edge transects, allowing for assessments of habitat plasticity and shifts through ontogeny (Artetxe-Arrate et al., 2019; Franco et al., 2019; Almeida et al., 2024b).

SQ has a typical estuarine environment with a positive water balance, influenced by tidal variations and a small channel. In contrast, AR is hypersaline due to its negative water balance, resulting from high evaporation and low fluvial and pluvial discharges (Kjerfve et al., 1996; Miranda et al., 2012; Dias et al., 2021). The distinct environmental conditions of these lagoon systems—SQ's estuarine and AR's hypersaline characteristics (Table 1), have been shown to significantly influence elemental incorporation into fish otoliths (Franco et al., 2019; Almeida et al., 2024a, 2024b).

Otolith Sr/Ca is widely recognized as a salinity proxy (Campana, 1999). Our Sr/Ca profiles measured in age 2^+ year old *P. courbina* individuals caught in SQ and AR demonstrate fluctuations between water masses of differing salinity in both lagoon systems. Our profiles are similar to those of *P. cromis* indicating the use of estuarine areas during early life stages (Rooker et al., 2004), and support that profile analysis can trace large-scale habitat transitions, such as between marine and estuarine habitats. Estuary-dependent behavior, based on otolith Sr/Ca profiles of comparable amplitude, has also been observed in another sciaenid, *Micropogonias furnieri*, which uses both SQ and AR lagoon systems (Franco et al., 2019). Our results are also consistent with earlier *P. courbina* studies indicating that adult individuals close to the age of sexual maturity ($A_{50} = 2$ years; TL $= 30.8 \pm 0.5$ cm) can make longer migrations to marine coastal areas (Urteaga and Perrotta, 2001; Macchi et al., 2002; Haimovici and Cardoso, 2017).

In coastal systems, high Sr/Ca ratios in otoliths typically indicate marine habitats, whereas higher Ba/Ca ratios suggest freshwater or brackish environments (Avigliano et al., 2015a). Integration of these element/Ca ratios may distinguish water mass habitats within and between lagoon systems (Elsdon et al., 2008). Fluctuations in Ba/Ca and Sr/Ca suggest transitions between freshwater, brackish, and saline environments, with Ba/Ca often linked to estuarine waters rich in Ba (Campana et al., 2007; Crook et al., 2016). Microchemical analysis of *P. courbina* otoliths in the present study are consistent with an estuarine-dependent behavior during early life stages.

Otolith Ba/Ca has been shown to be closely associated with estuarine environments, as Ba tends to be more abundant in low-salinity areas influenced by freshwater and fluvial inputs (Bouchard et al., 2015). Highest otolith Ba concentrations in this study were found in individuals caught in Saquarema lagoon, a typical estuarine system characterized by patterns of restricted movement of mesohaline waters. Significant Ba peaks occurring at the end of age 1 and after age 2^+ individuals support the estuarine dependence of *P. courbina*, as similar movement patterns across salinity habitats have been documented for other species in estuarine zones (*e.g*, European eels, Tabouret et al. (2010); Kuhlia species, Feutry et al., 2012; silversides, Avigliano et al. (2017). Franco et al. (2019) also described the migratory behavior of *Micropogonias furnieri* in bays and the Araruama lagoon at different ages. Collectively, these studies highlight the significance of the Ba/Ca ratio as an indicator of

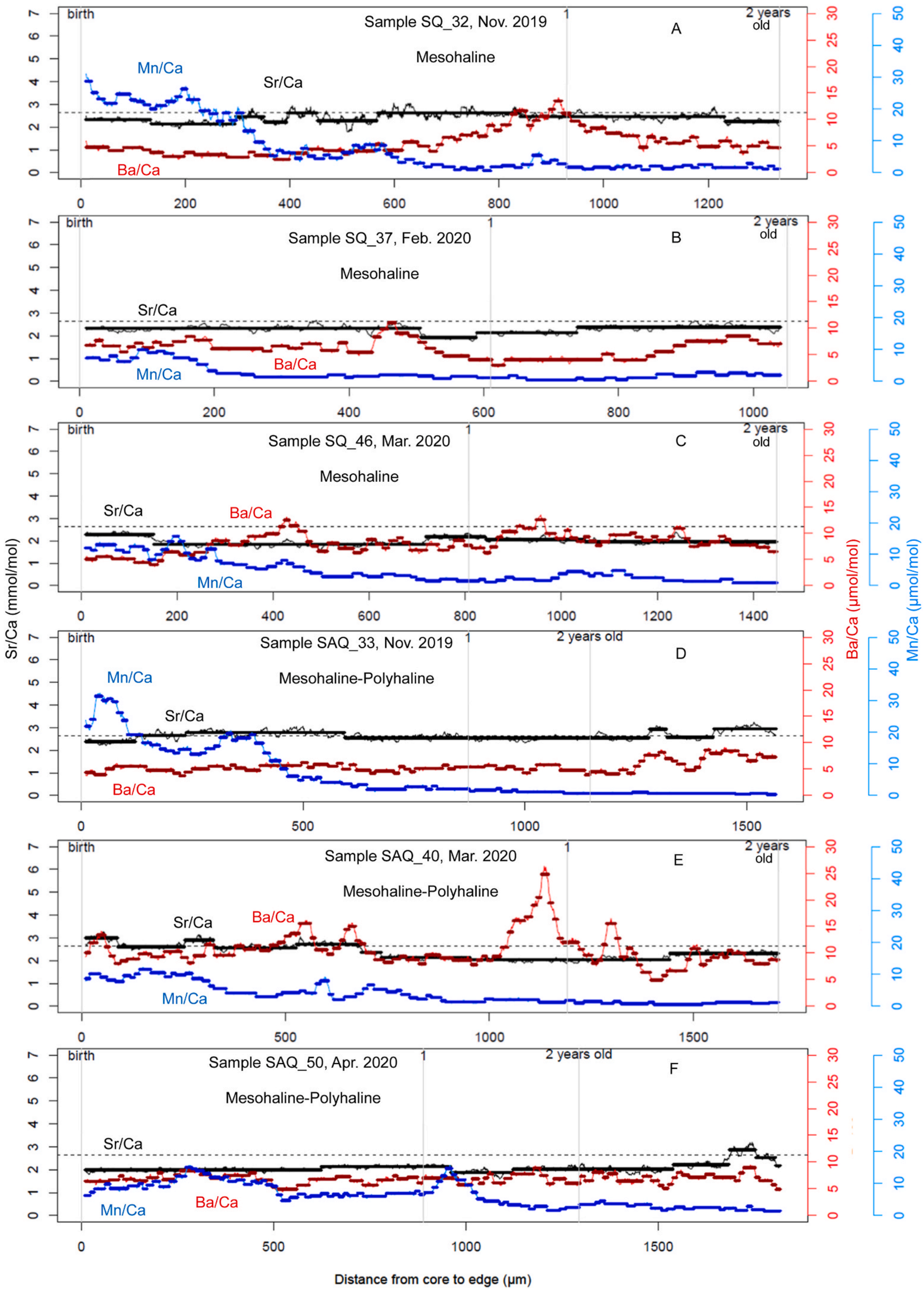

Fig. 5. Individual otolith microchemical profiles (Ba/Ca: red; Mn/Ca: blue; Sr/Ca: black) and changepoints of *Pogonias courbina* individuals captured in Saquarema (SQ), classified into two movement patterns: (1) mesohaline in A–C; and (2) mesohaline–polyhaline in D–F. The dashed horizontal line indicates the Sr/Ca-based salinity threshold (2.64 mmol/mol) separating lower mesohaline from higher polyhaline water masses. Vertical lines indicate specimen age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

habitat utilization and movement in estuarine-dependent species.

Otolith Mn has been shown to be closely related to fish growth and ontogeny, whereas Sr and Ba are more directly linked to concentrations of these elements in the surrounding water (Limburg et al., 2018; Franco et al., 2019; Soeth et al., 2020). Mn/Ca mainly displayed an inverse correlation with Sr/Ca ratios, especially in the AR, where variations in water masses were more pronounced. High dissolved Mn concentrations may enter estuarine environments in association with terrigenous input, but soon form insoluble oxide and hydroxide species that are scavenged (removed from the water column) by particle sedimentation, thereby decreasing Mn availability for uptake in otoliths in oxic water mass habitats (Thomas and Bendell-Young, 1999; Laugier et al., 2015; Aschenbrenner et al., 2016). While hypoxic conditions cause high Mn bioavailability, Saquarema lagoon presents larger areas of anoxic environments compared to Araruama, such as mangroves and swamps, resulting in variations in the Mn/Ca otolith elemental ratios (Limburg et al., 2015; Reis-Santos et al., 2022; Almeida et al., 2024b). High Mn/Ca relative to Sr/Ca observed in study individuals caught in Saquarema and Araruama lagoons indicate that *P. courbina* utilizes these environments as nurseries during its early years.

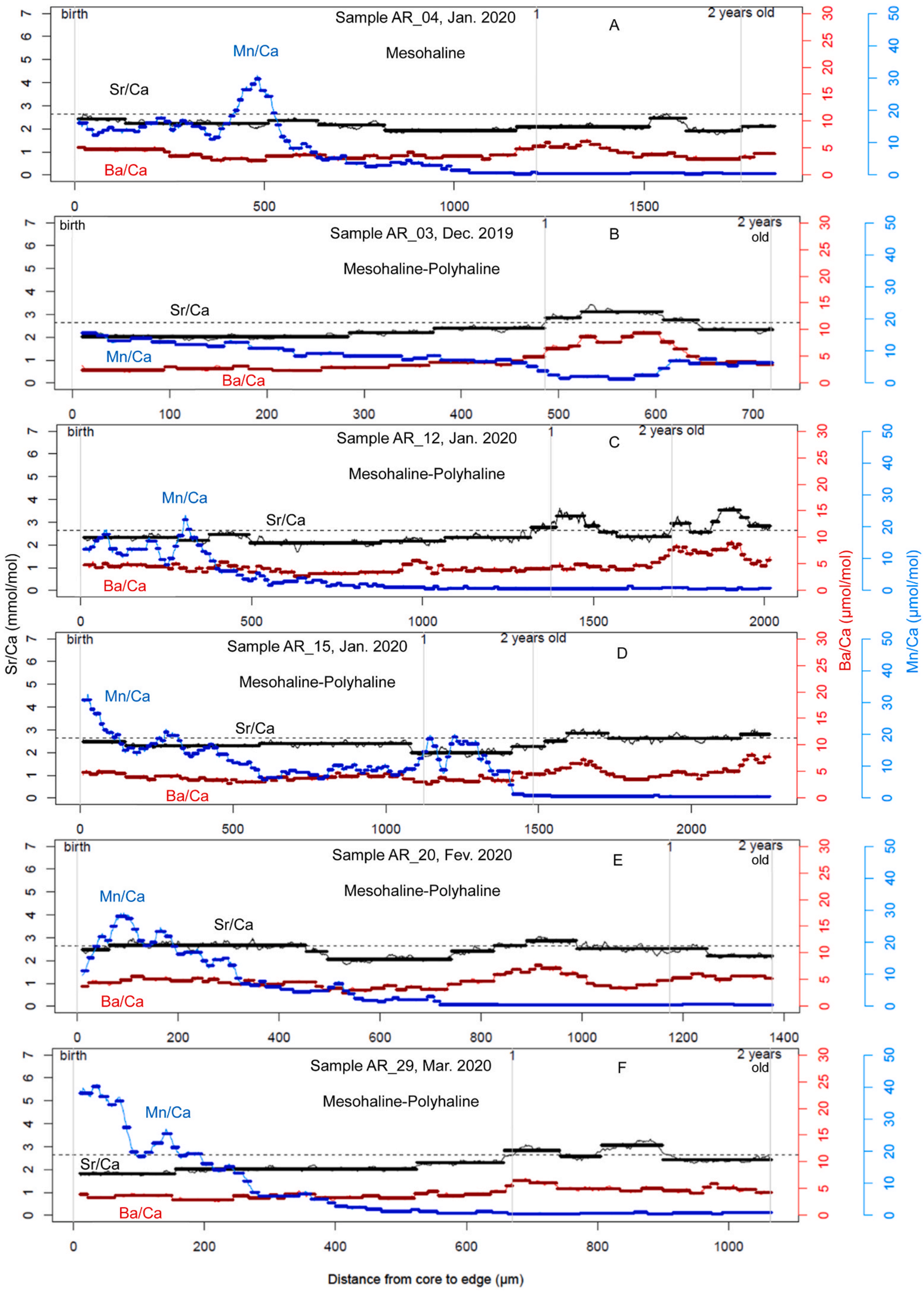

Fig. 6. Individual otolith microchemical profiles (Ba/Ca: red; Mn/Ca: blue; Sr/Ca: black) and changepoints of *Pogonias courbina* individuals captured in Araruama (AR), classified into two movement patterns: (1) mesohaline in A; and (2) mesohaline–polyhaline in B–F. The dashed horizontal line indicates the Sr/Ca-based salinity threshold (2.64 mmol/mol) separating lower mesohaline from higher polyhaline water masses. Vertical lines indicate specimen age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Relative and absolute frequency of the movement patterns of *Pogonias courbina* in the two lagoon systems of eastern Rio de Janeiro, Brazil.

Lagoon System	Mesohaline (M)	Mesohaline-Polyhaline (MP)
Saquarema (SQ)	50 % (10)	50 % (10)
Araruama (AR)	5 % (1)	95 % (19)
Total N	11	29
Total %	27.5 %	72.5 %

Mn in fish otoliths has also been linked to rapid growth and endogenous metabolic factors (yolk feeding—maternal effect), particularly during early developmental stages, from larval settlement to juvenile phases (Liberoff et al., 2014; Artetxe-Arrate et al., 2021). Mn acts as a co-factor of a biomineralization protein, extracellular serine threonine protein kinase FAM20C, found in otoliths (Tagliabracci et al., 2012; Thomas et al., 2019; Hüssy et al., 2021). Mn in primordial regions of larval Pacific cod otoliths is 20–100 times higher than concentrations found in older growth (DiMaria et al., 2010). Mn/Ca peaks are documented in the otolith primordium of various species, including *Clupea* *harengus* (Brophy et al., 2004), *Oxylebius pictus, Dascyllus marginatus, Stegastes beebei, Thalassoma bifasciatum, Galaxias maculatus*, and *Sebastes atrovirens* (Ruttenberg et al., 2005), as well as *Sicydium punctatum* and *Sillaginodes punctatus* (Rogers et al., 2019). Elevated Mn/Ca may indicate periods of intense somatic growth and high protein synthesis, reflecting significant metabolic changes during the transition from larval to juvenile stages (Avigliano et al., 2021). Our *P. courbina* microchemical results demonstrate elevated Mn/Ca ratios with a decreasing trend until age 2^+, along with pronounced peaks near the otolith nucleus. These patterns may indicate that Mn uptake follows an endogenous pathway associated with an ontogenetic shift in axial growth, namely rapid protein accumulation before a more crystalline mode of otolith formation begins.

Our documented Mn/Ca, Ba/Ca, and Sr/Ca profiles for *P. courbina* show clear variations between birth and age 2^+, suggesting that the incorporation of these elements may be influenced by both endogenous and exogenous factors, such as the physicochemical characteristics of the water masses in each lagoon system (Sturrock et al., 2015; Avigliano et al., 2021; Hüssy et al., 2021). Statistical comparison of these profiles identified two movement patterns, between mesohaline and polyhaline waters, reflecting the species' ability to transition between areas with different salinity gradients, during development. The mesohaline pattern was associated with the early stages of development, while later alternating pattern between mesohaline and polyhaline waters are consistent with wider movements toward areas with greater marine influence, possibly suggesting an exit from the lagoon system, especially in Saquarema, where this salinity gradient is well-defined.

In summary, our study demonstrates that *P. courbina* exhibits significant plasticity in habitat use, with distinct movement profiles, which reduces the risk of negative impacts on its populations (Almeida et al., 2023), as such behavioral diversity increases the resilience of the species to environmental fluctuations and anthropogenic disturbances. Furthermore, this adaptive flexibility and environmental plasticity already reported for other fish species (Wright et al., 2018; Daros et al., 2016; Ferreira et al., 2023), is essential in maintaining population stability, as it enables individuals to move through dynamic environments, ensuring survival under varied ecological conditions.

CRediT authorship contribution statement

Paulo Roberto Camponez de Almeida: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Alberto Teodorico Correia:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing. **Felipe Douglas Mendonça Cadilho:** Formal analysis, Investigation. **Nathan Miller:** Formal analysis, Resources, Writing – review & editing. **Cassiano Monteiro-Neto:** Project administration, Supervision, Writing – review & editing. **Marcus Rodrigues da Costa:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2025.109695.

Data availability

Data will be made available on request.

References

Almeida, P.R.C., Costa, M.R., Andrade, D.H., Monteiro, L.A.F., Penetra, E.J.G., Nascimento, C.M.O., Pinto, S.M., Ribeiro, A.T.R., Cadilho, F.D.M., Coutinho, R.D.S., Cirino, R.O.S., Barbosa, A.D., Bastos, A.L., Tubino, R.A., Monteiro-Neto, C., Correia, A.T., Tomás, A.R.G., Vaz-dos-Santos, A.M., Oliveira, N.B., Costa, P.A.G., Mattos, T.M., 2021. Ciclo de vida de espécies de importância ecológica e econômica. In: Costa, M.R., Tubino, R.A., Monteiro-Neto, C., Angelini, R. (Eds.), Pesca E Sustentabilidade: Passado, Presente E Futuro. AH Edições, pp. 71–92.

Almeida, P.R.C., Costa, M.R., de Oliveira, R.S.C., Almeida, A., Azevedo, R., Monteiro-Neto, C., Correia, A.T., 2023. The use of the shape and chemistry of fish otoliths as a subpopulational discrimination tool for *Eugerres brasilianus* in lagoon systems in the Southwest Atlantic Ocean. Fish. Res. 267, 106795. https://doi.org/10.1016/j.fishres.2023.106795.

Almeida, P.R.C., Costa, M.R., Ribeiro, A.T.R., Almeida, A., Azevedo, R., Monteiro-Neto, C., Correia, A.T., 2024a. Population structure and habitat connectivity of *Pogonias courbina* (Perciformes, Sciaenidae) in two Brazilian lagoon systems on south-east coast of Rio de Janeiro, Brazil, inferred from otolith shape and elemental signatures. J. Sea Res., 102500 https://doi.org/10.1016/j.seares.2024.102500.

Almeida, P.R.C., Costa, M.R., Coutinho, R.D.S., Méndez-Vicente, A., Castro, J.P., Monteiro-Neto, C., et al., 2024b. Use of otolith microchemistry signatures to assess the habitat use of *Centropomus undecimalis* in lagoon systems of the Southwest Atlantic. Reg. Stud. Mar. Sci. 73, 103470. https://doi.org/10.1016/j.rsma.2024.103470.

Artetxe-Arrate, I., Fraile, I., Crook, D.A., Zudaire, I., Arrizabalaga, H., Greig, A., Murua, H., 2019. Otolith microchemistry: a useful tool for investigating stock structure of yellowfin tuna (*Thunnus albacares*) in the Indian Ocean. Mar. Freshw. Res. 70 (12), 1708–1721. https://doi.org/10.1071/MF19067.

Artetxe-Arrate, I., Fraile, I., Farley, J., Darnaude, A.M., Clear, N., Rodríguez-Ezpeleta, N., et al., 2021. Otolith chemical fingerprints of skipjack tuna (*Katsuwonus pelamis*) in the Indian Ocean: first insights into stock structure delineation. PLoS One 16 (3), e0249327. https://doi.org/10.1371/journal.pone.0249327.

Aschenbrenner, A., Ferreira, B.P., Rooker, J.R., 2016. Spatial and temporal variability in the otolith chemistry of the Brazilian snapper *Lutjanus alexandrei* from estuarine and coastal environments. J. Fish. Biol. 89 (1), 753–769. https://doi.org/10.1111/jfb.13003.

Avigliano, E., Callicó-Fortunato, R., Buitrago, J., Volpedo, A.V., 2015a. Is the otolith microchemistry (Sr:Ca and ba:ca ratios) useful to identify *Mugil curema* populations in the southwestern Caribbean Sea? Braz. J. Biol. 75 (4), S41–S55. https://doi.org/10.1590/1519-6984.01014.

Avigliano, E., Saez, M.B., Rico, R., Volpedo, A.V., 2015b. Use of otolith strontium: calcium and zinc:calcium ratios as an indicator of the habitat of *Percophis brasiliensis* Quoy & Gaimard, 1825 in the southwestern Atlantic Ocean. Neotrop. Ichthyol. 13 (1), 187–194. https://doi.org/10.1590/1982-0224-20130235.

Avigliano, E., Leisen, M., Romero, R., Carvalho, B., Velasco, G., Vianna, M., Barra, F., Volpedo, A.V., 2017. Fluvio-marine travelers from South America: cyclic amphidromy and freshwater residency, typical behaviors in *Genidens barbus* inferred by otolith chemistry. Fish. Res. 193, 184–194. https://doi.org/10.1016/j.fishres.2017.04.011.

Avigliano, E., Alves, N.M., Rico, M.R., Ruarte, C.O., D'Atri, L., Méndez, A., et al., 2021. Population structure and ontogenetic habitat use of *Micropogonias furnieri* in the Southwestern Atlantic Ocean inferred by otolith chemistry. Fish. Res. 240, 105953. https://doi.org/10.1016/j.fishres.2021.105953.

Azpelicueta, M.D.L.M., Delpiani, S.M., Cione, A.L., Oliveira, C., Marceniuk, A.P., Díaz de Astarloa, J.M., 2019. Morphology and molecular evidence support the validity of *Pogonias courbina* (Lacepède, 1803) (Teleostei: sciaenidae), with a redescription and neotype designation. PLoS One 14 (6), e0216280. https://doi.org/10.1371/journal.pone.0216280.

Barbieri, E., Coe-Neto, R., 1999. Spatial and temporal variation of rainfall of the East Fluminense coast and Atlantic Serra do Mar, State of Rio de Janeiro, Brazil. In: Bidone, Abrão, J.J. (Eds.), Environmental Geochemistry of Coastal Lagoon Systems of Rio De Janeiro, Brazil. Niterói. FINEP, pp. 47–56.

Blasina, G.E., Barbini, S.A., Díaz de Astarloa, J.M., 2010. Trophic ecology of the black drum, *Pogonias cromis* (Sciaenidae), in Mar Chiquita coastal lagoon (Argentina).

J. Appl. Ichthyol. 26 (4), 528–534. https://doi.org/10.1111/j.1439-0426.2010.01459.x.

Bouchard, C., Thorrold, S.R., Fortier, L., 2015. Spatial segregation, dispersion and migration in early stages of polar cod *Boreogadus saida* revealed by otolith chemistry. Mar. Biol. 162, 855–868. https://doi.org/10.1007/s00227-015-2629-5.

Brasil. Ministério do Meio Ambiente (MMA). 2014. Portaria MMA Nº 445, de 17 de Dezembro de 2014. Lista Nacional Oficial de Espécies da Fauna Ameaçadas de Extinção - Peixes e Invertebrados Aquáticos. Diário Oficial da União, Seção 1, Brasília, DF, 18 dez. 2014. p. 126.

Brennan, S.R., Fernandez, D.P., Zimmerman, C.E., Cerling, T.E., Brown, R.J., Wooller, M. J., 2015. Strontium isotopes in otoliths of a non-migratory fish (slimy sculpin): Implications for provenance studies. Geochimica et Cosmochimica Acta 149, 32–45.

Brophy, D., Jeffries, T.E., Danilowicz, B.S., 2004. Elevated manganese concentrations at the cores of clupeid otoliths: possible environmental, physiological, or structural origins. Mar. Biol. 144, 779–786. https://doi.org/10.1007/s00227-003-1240-3.

Cadilho, F.D.M., Almeida, P.R.C., Costa, M.R., 2023. CPecopesca: pacote para executar o changepoint por distância no eixo x. v1.1.0. URL: https://github.com/FelipeCadilho/CPecopesca.

Camara, E.M., de Andrade-Tubino, M.F., Franco, T.P., Araújo, F.G., 2020. Multilevel decomposition of spatial and environmental effects on nearshore fish assemblages in tropical semi-enclosed ecosystems. Estuar. Coast Shelf Sci. 237, 106691. https://doi.org/10.1016/j.ecss.2020.106691.

Campana, S.E., 1999. Chemistry and composition of fish otoliths: pathways, mechanisms and applications. Mar. Ecol. Prog. Ser. 188, 263–297. https://doi.org/10.3354/meps188263.

Campana, S.E., Valentin, A., Sévigny, J.M., Power, D., 2007. Tracking seasonal migrations of redfish (Sebastes spp.) in and around the Gulf of st. Lawrence using otolith elemental fingerprints. Can. J. Fish. Aquat. Sci. 64 (1), 6–18. https://doi.org/10.1139/f06-162.

Chao, N.L., Frédou, F.L., Haimovici, M., Peres, M.B., Polidoro, B., Raseira, M., et al., 2015. A popular and potentially sustainable fishery resource under pressure–extinction risk and conservation of Brazilian Sciaenidae (Teleostei: perciformes). Glob. Ecol. Conserv. 4, 117–126. https://doi.org/10.1016/j.gecco.2015.06.002.

Corrêa, G.M.S., Coletto, J.L., Castello, J.P., Miller, N.R., Tubino, R.A., Monteiro-Neto, C., Costa, M.R., 2022. Identification of fish stock based on otolith as a natural marker: the case of *Katsuwonus pelamis* (Linnaeus, 1758) in the Southwest Atlantic Ocean. Fish. Res. 255, 106436. https://doi.org/10.1016/j.fishres.2022.106436.

Crook, D.A., Lacksen, K., King, A.J., Buckle, D.J., Tickell, S.J., Woodhead, J.D., et al., 2016. Temporal and spatial variation in strontium in a tropical river: implications for otolith chemistry analyses of fish migration. Can. J. Fish. Aquat. Sci. 74 (4), 533–545. https://doi.org/10.1139/cjfas-2016-0153.

Dantas, D.V., Barletta, M., 2016. Habitat use by *Centropomus undecimalis* in a rocky area of estuarine beach in north-east Brazil. J. Fish. Biol. 89 (1), 793–803. https://doi.org/10.1111/jfb.13001.

Daros, F.A., Spach, H.L., Correia, A.T., 2016. Habitat residency and movement patterns of *Centropomus parallelus* juveniles in a subtropical estuarine complex. J. Fish. Biol. 88 (5), 1796–1810. https://doi.org/10.1111/jfb.12944.

Dias, F.F., Nascimento, V., Costa, B.R., Vargas, R., Costa, M.R., Monteiro-Neto, C., Tubino, R.A., 2021. Lagoas costeiras do leste fluminense: origem, evolução, importância e aspectos demográficos. In: Costa, M.R., Monteiro-Neto, C., Tubino, R. A., Angelini, R. (Eds.), Pesca E Sustentabilidade: Passado, Presente E Futuro. Interciência, pp. 21–34.

DiMaria, R.A., Miller, J.A., Hurst, T.P., 2010. Temperature and growth effects on otolith elemental chemistry of larval Pacific cod, *Gadus macrocephalus*. Environ. Biol. Fish. 89, 453–462. https://doi.org/10.1007/s10641-010-9665-2.

Elliott, M., Whitfield, A.K., Potter, I.C., Blaber, S.J., Cyrus, D.P., Nordlie, F.G., Harrison, T.D., 2007. The guild approach to categorizing estuarine fish assemblages: a global review. Fish Fish. 8 (3), 241–268. https://doi.org/10.1111/j.1467-2679.2007.00253.x.

Elsdon, T.S., Wells, B.K., Campana, S.E., Gillanders, B.M., Jones, C.M., Limburg, K.E., et al., 2008. Otolith chemistry to describe movements and life-history parameters of fishes: hypotheses, assumptions, limitations and inferences. In: Oceanography and Marine Biology. CRC Press, pp. 303–336.

Ferreira, I., Daros, F.A., Moreira, C., Feijó, D., Rocha, A., Mendez-Vicente, A., Castro, J. P., Correia, A.T., 2023. Is *Chelidonicthys lucerna* (Linnaeus, 1758) a marine estuarine dependent fish? Insights from saccular otolith microchemistry. Fishes 8, 383. https://doi.org/10.3390/fishes8070383.

Feutry, P., Tabouret, H., Maeda, K., Pécheyran, C., Keith, P., 2012. Diadromous life cycle and behavioural plasticity in freshwater and estuarine Kuhliidae species (Teleostei) revealed by otolith microchemistry. Aquat. Biol. 15 (3), 195–204. https://doi.org/10.3354/ab00423.

Fowler, A.M., Smith, S.M., Booth, D.J., Stewart, J., 2016. Partial migration of grey mullet (*Mugil cephalus*) on Australia's east coast revealed by otolith chemistry. Mar. Environ. Res. 119, 238–244. https://doi.org/10.1016/j.marenvres.2016.06.010.

Franco, T.P., Albuquerque, C.Q., Santos, R.S., Saint'Pierre, T.D., Araújo, F.G., 2019. Leave forever or return home? The case of the whitemouth croaker *Micropogonias furnieri* in coastal systems of southeastern Brazil indicated by otolith microchemistry. Mar. Environ. Res. 144, 28–35. https://doi.org/10.1016/j.marenvres.2018.11.015.

Franco, T.P., Vilasboa, A., Araújo, F.G., Gama, J.M., Correia, A.T., 2023. Identifying Whitemouth Croaker (*Micropogonias furnieri*) Populations along the Rio de Janeiro Coast, Brazil, through Microsatellite and Otolith Analyses. Biology 12 (3), 360. https://doi.org/10.3390/biology12030360.

Franzen, M.O., Muelbert, J.H., Fernandes, E.H., 2019. Influence of wind events on the transport of early stages of *Micropogonias furnieri* (Desmarest, 1823) to a subtropical estuary. Latin American Journal of Aquatic Research 47 (3), 536–546. https://doi.org/10.3856/vol47-issue3-fulltext-15.

Friedman, A.G., 2011. Lagoons: Biology, Management and Environmental Impact. Nova Science Pub Inc, UK, p. 493. Edition.

Haimovici, M., Cardoso, L.G., 2017. Long-term changes in the fisheries in the Patos Lagoon estuary and adjacent coastal waters in Southern Brazil. Mar. Biol. Res. 13 (1), 135–150. https://doi.org/10.1080/17451000.2016.1228978.

Hellstrom, J., Paton, C., Woodhead, J., Hergt, J., 2008. CHAPTER A9. IOLITE: SOFTWARE FOR SPATIALLY RESOLVED LA–(QUAD and MC)–ICP–MS ANALYSIS.

Herbst, D., Hanazaki, N., 2014. Local ecological knowledge of fishers about the life cycle and temporal patterns in the migration of mullet (*Mugil liza*) in Southern Brazil. Neotrop. Ichthyol. 12, 879–890. https://doi.org/10.1590/1982-0224-20130156.

Höpker, S.N., Wu, H.C., Lucassen, F., Sadio, O., Brochier, T., Nuworkpor, I.Y., et al., 2022. Sr isotope ratios (87Sr/86Sr) in water and fish otoliths as estuarine salinity tracers: case studies from three NW African Rivers. Estuaries Coasts 45 (6), 1780–1802. https://doi.org/10.1007/s12237-021-01041-x.

Hüssy, K., Limburg, K.E., De Pontual, H., Thomas, O.R., Cook, P.K., Heimbrand, Y., Sturrock, A.M., 2021. Trace element patterns in otoliths: the role of biomineralization. Reviews in Fishery Science and Aquaculture 29 (4), 445–477. https://doi.org/10.1080/23308249.2020.1760204.

Ingram, B.L., Weber, P.K., 1999. Salmon origin in California's Sacramento–San Joaquin river system as determined by otolith strontium isotopic composition. Geology 27 (9), 851–854. https://doi.org/10.1130/0091-7613(1999)0272.3.co;2.

Killick, R., Eckley, I.A., 2014. changepoint: An R package for changepoint analysis. Journal of statistical software 58, 1–19.

Kjerfve, B., Schettini, C.A.F., Knoppers, B., Lessa, G., Ferreira, H.O., 1996. Hydrology and salt balance in a large, hypersaline coastal lagoon: Lagoa de Araruama, Brazil. Estuar. Coast Shelf Sci. 42 (6), 701–725. https://doi.org/10.1006/ecss.1996.0045.

Lacepède, B.G.E., 1803. Histoire naturelle des poissons 5, 1–803.

Laugier, F., Feunteun, E., Pécheyran, C., Carpentier, A., 2015. Life history of the Small Sandeel, *Ammodytes tobianus*, inferred from otolith microchemistry. A methodological approach. Estuar. Coast Shelf Sci. 165, 237–246. https://doi.org/10.1016/j.ecss.2015.05.022.

Liberoff, A.L., Miller, J.A., Riva-Rossi, C.M., Hidalgo, F.J., Fogel, M.L., Pascual, M.A., Tierney, K., 2014. Transgenerational effects of anadromy on juvenile growth traits in an introduced population of rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 71, 398–407. https://doi.org/10.1139/cjfas-2013-0466.

Limburg, K.E., Walther, B.D., Lu, Z., Jackman, G., Mohan, J., Walther, Y., et al., 2015. In search of the dead zone: use of otoliths for tracking fish exposure to hypoxia. J. Mar. Syst. 141, 167–178. https://doi.org/10.1016/j.jmarsys.2014.02.014.

Limburg, K.E., Wuenschel, M.J., Hüssy, K., Heimbrand, Y., Samson, M., 2018. Making the otolith magnesium chemical calendar-clock tick: plausible mechanism and empirical evidence. Reviews in Fisheries Science & Aquaculture 26 (4), 479–493. https://doi.org/10.1080/23308249.2018.1458817.

Lopes, M.S., Aguilera, O., Monteiro-Neto, C., Miller, N.R., Gaspar, M.D., Costa, M.R.D., 2023. Archaeological and modern whitemouth croaker fish (*Micropogonias furnieri*) of southeastern Brazil: a geochemical proxy for environmental preference. Holocene 33 (7), 890–902. https://doi.org/10.1177/09596836231163510.

Macchi, G.J., Acha, E.M., Lasta, C.A., 2002. Reproduction of black drum (*Pogonias cromis*) in the Rıo de la Plata estuary, Argentina. Fish. Res. 59 (1–2), 83–92. https://doi.org/10.1016/S0165-7836(01)00410.

Mansur, K., Guedes, E., Alves, M.G., Nascimento, V., Pressi, L.F., Costa Jr, N., Pessanha, A., Nascimento, L.H., Vasconcelos, G., 2012. Geoparque Costões e Lagunas do Estado do Rio de Janeiro (RJ). In: Schobbenhaus, C., Silva, C.R. (Eds.), (Orgs) Projeto Geoparques Do Brasil: Propostas. CPRM, Rio de Janeiro, pp. 686–745.

Menezes, R., Moura, P.E., Santos, A.C., Moraes, L.E., Condini, M.V., Rosa, R.S., Albuquerque, C.Q., 2021. (Lutjanus jocu) across the Abrolhos Bank shelf, eastern Brazil, inferred from otolith chemistry. *Estuarine*. Coastal and Shelf Science 263, 107637.

Militelli, M.I., Macchi, G.J., Rodrigues, K.A., 2013. Comparative reproductive biology of Sciaenidae family species in the Río de la Plata and Buenos Aires Coastal Zone, Argentina. J. Mar. Biol. Assoc. U. K. 93 (2), 413–423. https://doi.org/10.1017/S0025315412001488.

Miranda, L.B., Castro, B.M., Kjerfve, B., 2012. Princípios de oceanografia física de estuários, second ed. Editora da USP, São Paulo.

Nagelkerken, I., 2009. Ecological Connectivity Among Tropical Coastal Ecosystems. Springer, Drodrecht, p. 615.

Ng, C.Z., Reis-Santos, P., Gonzalez, Gillanders, B.M., Saleh, M.F., Ong, J.J., 2025. A non-linear statistical framework to investigate changes in life history patterns within and among fish populations. Reviews in Fish Biology and Fisheries 1–16.

Odell, J., Adams, D.H., Boutin, B., Collier II, W., Deary, A., Havel, L.N., Johnson Jr., J.A., Midway, S.R., Murray, J., Smith, K., Wilke, K.M., Yuen, M.W., 2017. Atlantic sciaenid habitats: a review of utilization, threats, and recommendations for conservation, management, and research. In: Atlantic States Marine Fisheries Commission Habitat Management Series No. 14, Arlington, VA.

Olsen, Z., McDonald, D., Bumguardner, B., 2018. Intraspecific variation in life history strategies and implications for management: a case study of black drum (*Pogonias cromis*) in the Upper Laguna Madre, Texas USA. Fish. Res. 207, 55–62. https://doi.org/10.1016/j.fishres.2018.06.009.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'hara, R.B., Oksanen, M.J., 2021. Package 'vegan'. Community Ecol. Package 2 (9), 1–295.

Pelage, L., Gonzalez, J.G., Le Loch, F., Ferreira, V., Munaron, J.-M., Lucena-Fredou, F., Fredou, T., 2021. Importance of estuary morphology for ecological connectivity with their adjacent coast: a case study in Brazilian tropical estuaries. Estuar. Coast Shelf Sci. 251, 107184. https://doi.org/10.1016/j.ecss.2021.107184.

Potter, I.C., Tweedley, J.R., Elliott, M., Whitfield, A.K., 2015. The ways in which fish use estuaries: a refinement and expansion of the guild approach. Fish Fish. 16 (2), 230–239. https://doi.org/10.1111/faf.12050.

R Development Core Team, 2025. R: a Language and Environment for Statistical Computing. R Foundation for statistical computing, Viena, Austria. http://www.R-project.org. (Accessed 1 March 2023).

Ramos, J.A.A., Barletta, M., Dantas, D.V., Lima, A.R.A., Costa, M.F., 2014. Trophic niche and habitat shifts of sympatric Gerreidae. J. Fish. Biol. 85 (5), 1446–1469. https://doi.org/10.1111/jfb.12499.

Ramos, J.A.A., Barletta, M., Dantas, D.V., Costa, M.F., 2016. Seasonal and spatial ontogenetic movements of Gerreidae in a Brazilian tropical estuarine ecocline and its application for nursery habitat conservation. J. Fish. Biol. 89 (1), 696–712. https://doi.org/10.1111/jfb.12872.

Reis-Santos, P., Gillanders, B.M., Sturrock, A.M., Izzo, C., Oxman, D.S., Lueders-Dumont, J.A., Walther, B.D., 2022. Reading the biomineralized book of life: expanding otolith biogeochemical research and applications for fisheries and ecosystem-based management. Rev. Fish Biol. Fish. 1–39. https://doi.org/10.1007/s11160-022-09729-4.

Rogers, T.A., Fowler, A.J., Steer, M.A., Gillanders, B.M., 2019. Discriminating natal source populations of a temperate marine fish using larval otolith chemistry. Front. Mar. Sci. 6, 1–17. https://doi.org/10.3389/fmars.2019.00711.

Rooker, J.R., Kraus, R.T., Secor, D.H., 2004. Dispersive behaviors of black drum and red drum: is otolith Sr: ca a reliable indicator of salinity history? Estuaries 27, 334–341. https://doi.org/10.1007/BF02803389.

Ruttenberg, B.I., Hamilton, S.L., Hickford, M.J., Paradis, G.L., Sheehy, M.S., Standish, J. D., et al., 2005. Elevated levels of trace elements in cores of otoliths and their potential for use as natural tags. Mar. Ecol. Prog. Ser. 297, 273–281. https://doi.org/10.3354/meps297273.

Santos, P.R., Einhardt, A.C.M.C., Velasco, G., 2016. A pesca artesanal da miragaia (*Pogonias cromis*, Sciaenidae) no estuário da Lagoa dos Patos, Brasil. Boletim do Instituto de Pesca 42 (1), 89–101. https://doi.org/10.20950/1678.2305.2016v42n1p89.

Santos, P.R., Velasco, G., 2021. Reduction of reproductive parameters of *Pogonias courbina* (Perciformes, Sciaenidae) in southern Brazil. Reg. Stud. Mar. Sci. 41, 101590. https://doi.org/10.1016/j.rsma.2020.101590.

Santana, F.M., Morize, E., Labonne, M., Lessa, R., Clavier, J., 2018. Connectivity between the marine coast and estuary for white mullet (*Mugil curema*) in northeastern Brazil revealed by otolith Sr: ca ratio. Estuar. Coast Shelf Sci. 215, 124–131. https://doi.org/10.1016/j.ecss.2018.09.032.

Secor, D.H., Dean, J.M., Laban, E.H., 1992. Otolith removal and preparation for microstructural examination. In: Stevenson, D.K., Campana, S.E. (Eds.), Otolith Microstructure Examination and Analysis. Canadian Special Publication of Fisheries and Aquatic Sciences, Otawa, pp. 19–57.

Soeth, M., Spach, H.L., Daros, F.A., Castro, J.P., Correia, A.T., 2020. Use of otolith elemental signatures to unravel lifetime movement patterns of Atlantic spadefish, Chaetodipterus faber, in the Southwest Atlantic Ocean. Journal of Sea Research 158, 101873.

Sturrock, A.M., Hunter, E., Milton, J.A., Johnson, R.C., Waring, C.P., Trueman, C.N., 2015. Quantifying physiological influences on otolith microchemistry. Methods Ecol. Evol. 6 (7), 806–816. https://doi.org/10.1111/2041-210X.12381.

Tabouret, H., Bareille, G., Claverie, F., Pécheyran, C., Prouzet, P., Donard, O.F.X., 2010. Simultaneous use of strontium: calcium and barium: calcium ratios in otoliths as markers of habitat: application to the European eel (*Anguilla anguilla*) in the Adour basin, South West France. Mar. Environ. Res. 70 (1), 35–45. https://doi.org/10.1016/j.marenvres.2010.02.006.

Tagliabracci, V.S., Engel, J.L., Wen, J., Wiley, S.E., Worby, C.A., Kinch, L.N., et al., 2012. Secreted kinase phosphorylates extracellular proteins that regulate biomineralization. Science 336 (6085), 1150–1153. https://doi.org/10.1126/science.1217817.

Thomas, C.A., Bendell-Young, L.I., 1999. The significance of diagenesis versus riverine input in contributing to the sediment geochemical matrix of iron and manganese in an intertidal region. Estuar. Coast Shelf Sci. 48 (6), 635–647. https://doi.org/10.1006/ecss.1998.0473.

Thomas, O.R., Swearer, S.E., Kapp, E.A., Peng, P., Tonkin-Hill, G.Q., Papenfuss, A., et al., 2019. The inner ear proteome of fish. FEBS J. 286 (1), 66–81. https://doi.org/10.1111/febs.14715.

Tubino, R.A., Abreu, M.D., Marco, C., Monteiro-Neto, C., Costa, M.R., 2021. A produção pesqueira nos sistemas lagunares do leste fluminense. In: Costa, M.R., Tubino, R.A., Monteiro-Neto, C., Angelini, R. (Eds.), Pesca e sustentabilidade: Passado, presente e futuro. AH Edições, Rio de Janeiro, pp. 111–127.

Urteaga, J.R., Perrotta, R.G., 2001. Estudio preliminar del crecimiento, area de distribucion y pesca de la corvina negra (*Pogonias cromis*) en el litoral de la provincia de Buenos Aires. Mar del Plata, Argentina: Inidep Inf. Tec. 43, 22.

Velasco, G., Reis, E.G., Vieira, J.P., 2007. Calculating growth parameters of *Genidens barbus* (Siluriformes, Ariidae) using length composition and age data. J. Appl. Ichthyol. 23 (1), 64–69. https://doi.org/10.1111/j.1439-0426.2006.00793.x.

Vignon, M., 2015. Extracting environmental histories from sclerochronological structures — recursive partitioning as a mean to explore multi-elemental composition of fish otolith. Ecol. Inform. 30, 159–169. https://doi.org/10.1016/j.ecoinf.2015.10.002.

Wright, P.J., Régnier, T., Gibb, F.M., Augley, J., Devalla, S., 2018. Assessing the role of ontogenetic movement in maintaining population structure in fish using otolith microchemistry. Ecol. Evol. 8 (16), 7907–7920. https://doi.org/10.1002/ece3.4186.