



Use of otolith microchemistry signatures to assess the habitat use of *Centropomus undecimalis* in lagoon systems of the southwest Atlantic

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ARTICLE INFO

Keywords:

Centropomidae
Sagittae
Natural tags
Chemical analyses

ABSTRACT

The common snook, *Centropomus undecimalis*, is a catadromous species that is economically important for the southwest Atlantic artisanal and recreational fisheries. Their complex movement patterns and habitat use preferences are not fully understood in the Brazilian Atlantic waters, raising some issues regarding the rational and sustainable management of the fisheries. The present study aimed to identify the habitat use by *C. undecimalis* individuals captured in four coastal lagoon systems in the Eastern Rio de Janeiro state, Brazil. Sixty individuals were collected in the lagoon systems of Itaipu, Maricá, Saquarema and Araruama, between November 2019 and March 2020. A selection of 15 individuals per site from the same age group (3 years old), following age estimation by counting the annual growth increments, were used. Elemental signatures of the otolith's cores and edges were obtained using laser ablation inductively coupled-plasma mass spectrometry (LA-ICP-MS). Data were analyzed using univariate and multivariate statistics to assess the degree of separation among individuals regarding the natal origin (otolith cores) and moment of capture (otolith edges) from the sampling sites. Elemental signatures exhibited distinct spatial patterns, driven by Ba/Ca, Li/Ca and Sr/Ca in the otolith cores and Ba/Ca, Li/Ca, Mn/Ca and Sr/Ca in the edges. A low reclassification was recorded for the otolith's core (overall: 45%; by lagoon: 53% Saquarema, 53% Maricá, 47% Itaipu and 27% Araruama). However, a highest overall reclassification was observed for the otolith's edge (overall: 65%; by lagoon: 73% Itaipu, 73% Saquarema, 60% Maricá, and 53% Araruama). Differences between otolith core and edge signatures within locations were detected for Ba/Ca, Cu/Ca, Li/Ca, Mn/Ca and Sr/Ca ratios. The results obtained indicate an ontogenetic habitat shift, with a similar natal origin of the individuals probably due to marine water influence, and discrimination of heterogeneous juvenile fish groups driven by distinct phenotypic characteristics of the lagoons.

1. Introduction

The connectivity between the inshore waters and the nearby costal lagoons are important issues in defining the habitat use by fishes and to

estimate the nursery value of each feeding-growing area (Camara et al., 2021; Dantas and Barletta, 2016; Nagelkerken et al., 2005). The connectivity among adjacent nursery grounds through the larval and juvenile stages, as well as the ability of adults to disperse, are key-issues for

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<https://doi.org/10.1016/j.rsma.2024.103470>

Received 29 July 2023; Received in revised form 3 March 2024; Accepted 8 March 2024

Available online 11 March 2024

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marine fish populations (Sale et al., 2005; Kritzer and Sale, 2006; Camara et al., 2020). The connectivity between the nursery areas and the coastal fishing grounds shows the importance of these complex habitats for the replenishment of adult fish stocks (Vignon, 2012; Avigliano and Volpedo, 2016; Camara et al., 2021). The relevance of the estuaries as nursery grounds in supporting marine adult populations of fishes has long been of interest to the scientific community, which showed that the use of segregated habitats during early life stages is a key ecological feature for some species (Beck et al., 2001; Able, 2005; Vasconcelos et al., 2011). All areas used by fishes during their life stages, from post-settlement to the subadult's phase, may be considered 'nursery' habitats (Brame et al., 2014). An estuarine nursery ground can be defined by a sheltered site with variable salinity, whose attributes coincide with behavioural mechanisms attracting young fish (Ley and Rolls, 2018). Ontogenetic links between spawning grounds, larval transport, juvenile and subadult habitats (nursery grounds) are highly relevant to a better understanding of the spatiotemporal characteristics of the coastal fish populations (Adams et al., 2009).

The common snook, *Centropomus undecimalis* (Bloch, 1792), is a demersal fish widely distributed in the coastal areas of the western Atlantic Ocean, being found from North Carolina (USA) to Southern Brazil (Muller and Taylor, 2000; Ley et al., 2010; Menezes et al., 2012). It is a catadromous species, moving between marine, estuarine and fresh water environments during different stages of its life cycle (Adams et al., 2009; Ley et al., 2010; Young et al., 2014), and may present distinct migratory patterns (contingents) among their regional populations (Ray, 2005; Pereira et al., 2015; Silva et al., 2019). *Centropomus undecimalis* is a protandrous hermaphrodite species, reaching sexual maturity first as a male (with 46.8 cm of total length), and posteriorly changing to female genera (at 75.9 cm of total length) (Taylor et al., 2000; Medeiros et al., 2021; Peters et al., 1998). In Brazil, *C. undecimalis* is an important halieutic resource, being captured mainly by artisanal (Begossi et al., 2012; Lima et al., 2018; Pereira et al., 2020) and recreational fisheries (Menezes et al., 2012; Barcelini et al., 2013; Freire et al., 2016). In Rio de Janeiro state, Brazil, according to the government agency, the artisanal fisheries recorded a decreasing trend of the landings in the last years: 51 tons in 2018, 43 tons in 2019, 49 tons in 2020 and 33 tons in 2021 (FIPERJ, 2022). In the lagoon systems of Eastern Rio de Janeiro were reported landings of approximately 12.8 tons between November 2019 and December 2020 (Tubino et al., 2021). However, intrinsic species attributes such as diadromous migratory behaviour, sequential hermaphroditism and high degree of association with complex habitats (wood debris, branches, beach rocks, mangrove prop roots and pneumatophores), let the stocks vulnerable to overfishing and habitat loss (Perera-Garcia et al., 2011; Dantas and Barletta, 2016; Lima et al., 2018).

The main nursery habitats for *C. undecimalis* are characterized by calm waters within protected shorelines, mud-sand substrata and marginal vegetation cover, and include coastal lagoons, mangroves, estuaries and beach rocks (Stevens et al., 2007; Dantas and Barletta, 2016). During the life cycle of *C. undecimalis*, adult individuals are found in rivers and coastal waters, when they migrate to spawn in high salinity coastal areas (tidal channels, bay channels, channels around nearshore islands and along beaches), with the eggs and larvae carried out to estuarine areas (Ley et al., 2010). The migratory pattern behaviour of *C. undecimalis* begins as a pelagic larvae that moves with the currents to estuarine nurseries, a pelagic juvenile that lives and feeds in tidal tributary systems, a small demersal juvenile that usually occupies upstream parts of tidal tributaries, and larger demersal juveniles that can occupy tidal tributaries, ponds, bays and coastal areas (Ley et al., 2010; Medeiros et al., 2021). The *C. undecimalis* juveniles have great environmental plasticity, being resilient to pH, conductivity and salinity variations that occur in coastal lagoons (Pereira et al., 2015). The juvenile and young adult stages of *C. undecimalis* may show regionally specialized behaviour among populations, leading to potential variation in habitat use (Stevens et al., 2007; Silva et al., 2019; Pereira et al.,

2020). The preference of the juveniles for more sheltered nursery habitats, such as mangrove roots and wooden debris, highlights the habitat complexity required by *C. undecimalis*, and the need for effective management plans for the conservation of estuaries and coastal ecosystems, which represent complex mosaics of habitats that provide refuge, food availability and allow connectivity for fishes and other aquatic organisms (Dantas and Barletta, 2016; Nagelkerken et al., 2005).

Fish otoliths could be used as natural tags to discriminate groups of individuals with intrinsic local characteristics associated to their interactions with the environment according to their life history, movement and ontogeny attributes (Avigliano et al., 2020; Correia et al., 2021; Shroeder et al., 2022). Otoliths are polycrystalline calcium carbonate structures located in the inner ear of fish that grow continuously and aggregate chemical elements present in the water, serving as tracers of the fish's use of the habitat (Izzo et al., 2018; Avigliano et al., 2019; Reis-Santos et al., 2022). Otoliths allow to infer about the particular characteristics of the habitats of individuals from the beginning to the end of their life cycle, making it possible to assess the movement of individuals among different habitats and identify their places of origin (Dahlgren et al., 2006; Reis-Santos et al., 2013; Daros et al., 2016). The multi-elemental signatures of otoliths at the beginning of the fish's life cycle (core), at the moment of capture (edge) or throughout its life-history (core-to-edge transect), allow us to identify nursery areas, distinct populations and movement patterns (Franco et al., 2019; Soeth et al., 2020; Moreira et al., 2022).

The present study aimed to identify the patterns of habitat use by *C. undecimalis* captured in four lagoon systems in the eastern Rio de Janeiro state, inferred by the elemental signatures of the core (natal origin) and edge (moment of capture) of otoliths of a particular fish year-class recruitment. The up-dated gathered information about the movement, connectivity and use of habitats by *C. undecimalis* will allow us to define appropriate management and conservation actions for fish and habitat protection, which due to their characteristic lifestyle habits (hermaphrodites and diadromous), make them vulnerable populations to overfishing and anthropic impacts.

2. Material and methods

2.1. Study area characterization

Centropomus undecimalis juveniles were collected in four lagoon systems distributed along the eastern coastal plain of the state of Rio de Janeiro, Brazil, located at the upper limit of the marine ecoregion of southeast Brazil, in the southwest Atlantic Ocean: 1) Itaipu, 2) Maricá, 3) Saquarema and 4) Araruama (Fig. 1; Table 1). The climate gradient in the study area varies from humid to semi-arid, being governed by the presence of the continental equatorial air mass in summer, and the tropical Atlantic air mass during the rest of the year, including the passage of cold fronts mainly during spring (Barbiéri and Coe Neto, 1999; Alvares et al., 2013). The geomorphological configuration, the nature and extent of tidal channels, the continental drainage runoff, and the high urbanization are some factors that determine the hydrodynamics of these systems (Dias et al., 2021). Variations in water level and salinity occur as a result of small-scale (e.g. meso-tides) and large-scale weather events (e.g. cold fronts), river runoff, changes in the hydrological gradient, as well as the strength and direction of winds (Mansur et al., 2012). These characteristics lead to salinity gradients that distinguish zones with different levels of fresh and salt water influence in these lagoon systems (Mansur et al., 2012).

Located in the Niterói city (516,981 inhabitants), the coastal lagoon of Itaipu is an estuarine ecosystem connected by artificial channels to the Piratininga lagoon (Camboatá channel) and to the sea (Itaipu channel) (Fig. 1). The surrounding area is intensely urbanised, but its shores are covered by some remnants of mangrove forests, aquatic (rooted) vegetation, trees, shrubs, grasses, bluff, and small sandy beaches (Barroso et al., 2000; Silva and Molisani, 2019) (Table 1).

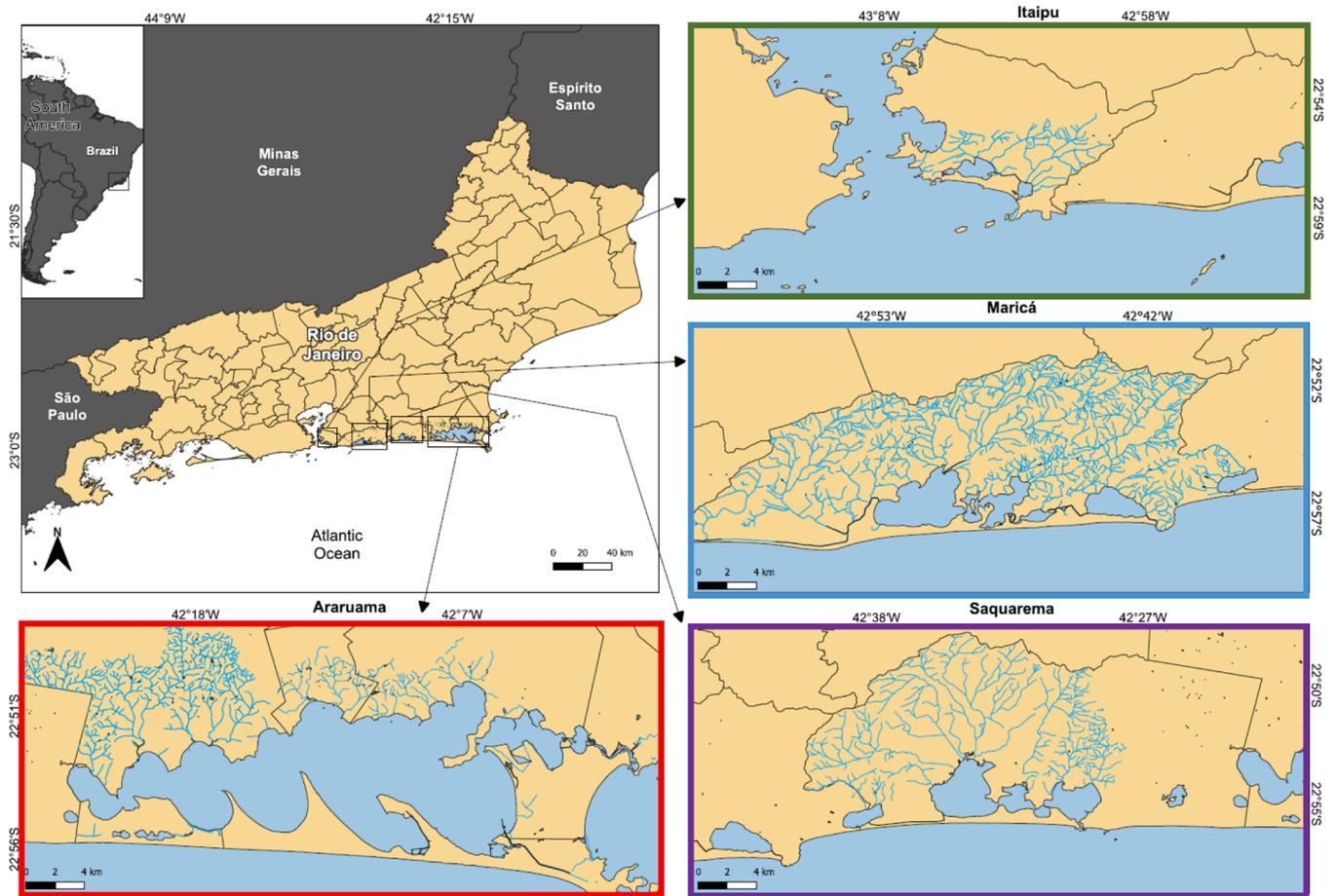


Fig. 1. Location of Brazil in the South America (inlet map), Rio de Janeiro state and the four sampling locations (Itaipu Lagoon System, Maricá Lagoon System, Saquarema Lagoon System and Araruama Lagoon System) of *Centropomus undecimalis* caught on the Southwest Atlantic from November 2019 to March 2020.

Table 1

Geographic coordinates descriptive parameters, trophic state and main anthropogenic contributions of the four lagoon systems of eastern, Rio de Janeiro, Brazil.

Lagoon system	Coordinates	Lagoon area (km ²)*	Drainage basin area (km ²)*	Depth range (m)*	Water residence time (days)*	Water temperature range (°C)**	Salinity range*	Average rainfall (mm. year ⁻¹)**	Trophic state***	Predominant anthropogenic contribution****
Itaipu	22° 96' S 43° 04' W	2	23	0.7–4.0	3	22–33	12–31	1.4	hypereutrophic	Domestic sewage
Maricá	22° 95' S 42° 69' W	34	330	0.5–2.0	28	21–33	3–25	1.3	hypereutrophic	Domestic sewage/ agricultural waste
Saquarema	22° 93' S 42° 49' W	21	215	0.6–2.4	27	18–33	9–34	1.3	supereutrophic	Domestic sewage/ agricultural waste
Araruama	22° 88' S 42° 01' W	225	285	0.5–18	84	21–29	12–60	0.9	supereutrophic	Domestic sewage/ agricultural waste/ mineral extraction: salt and shell limestone

Source: The authors based this information on data from Dias et al# (2021)*, Knoppers et al# 2009**, Silva and Molisani (2019)***, Dias et al., 2017 *** and Barroso et al# (2000)****.

Located in Maricá city (167,668 inhabitants), the Maricá lagoon system is an estuarine ecosystem composed of four elliptical cells. Three coastal lagoons (Maricá, Barra, and Padre; in a west-east direction), connected to each other, and connected intermittently through a channel to Guarapina lagoon (the last one). Guarapina lagoon is the only one that has an extensive channel of communication with the sea. Occasionally, the Barra lagoon can breach due to the narrowing between the sandbar and the lagoon's interior, caused by extreme events such as meteorological tides. This situation allows for a quick exchange of water between the innermost lagoons of this system (Fig. 1). Its surroundings

have a large urban occupation and some rural areas (Barroso et al., 2000; Silva and Molisani, 2019). Along its banks, there is a predominance of remnants of mangrove forests, rooted aquatic vegetation, and many non-vegetated areas (Costa et al. 2021).

Located in the Saquarema city (91,938 inhabitants), the Saquarema lagoon system is an estuarine ecosystem composed of four elliptical cells and/or coastal lagoons connected to each other and to the sea by an artificial channel (Fig. 1). Its surroundings have large rural occupation and some urban centers (Barroso et al., 2000; Silva and Molisani, 2019) (Table 1). Its margins are dominated by remnants of mangrove forests,

aquatic vegetation (rooted), shrubs, grasses, branches, and non-vegetated areas (Costa et al. 2021).

Inserted in the cities of Araruama (136,109 inhabitants), Iguaba Grande (29,344 inhabitants), São Pedro da Aldeia (107,556 inhabitants), Cabo Frio (234,077 inhabitants), and Arraial do Cabo (30,827 inhabitants), the lagoon system Araruama is an estuarine ecosystem composed of three compartments formed by seven elliptical cells interconnected with each other and to the sea through an artificial channel (Fig. 1). The surrounding areas are divided into urban and rural zones, with increasing urbanization driven by the continuous development of tourism in the region (Barroso et al., 2000) (Table 1). Along its shores, there are extensive sandy ridges, diverse vegetation such as mangroves, trees, bushes, grasses, as well as some stones and rocks (Costa et al. 2021).

2.2. Fish sampling and age estimates

Individuals were acquired monthly directly to artisanal fishermen in the four lagoon systems (Itaipu, Maricá, Saquarema and Araruama) between November 2019 and March 2020. Fishermen only operated in the respective lagoon systems, using fixed gill nets with mesh sizes varying between 30 and 70 mm. After the collection, specimens were stored in ice and transported to the laboratory. All individuals were measured in total length (TL, 0.1 cm) and weighed (TW, 0.1 g). A total of 60 pre-selected juvenile individuals ranging from 24.3 cm to 47.1 cm of TL were used in this study (Table 2). Thereafter, the sagittal otoliths were extracted with plastic tweezers, washed with distilled water to remove organic tissues and stored dry in plastic tubes. The pairs of sagittal otoliths (left and right sagittae) were distinguished according to the position of the rostrum and sulcus acusticus (Secor et al., 1992). Only well preserved and entire otoliths were used for microchemical analyses.

For age readings, otoliths were positioned with the sulcus acusticus down, under transmitted light using a Leica S9i stereoscopic microscope with 6X magnification (Vaz-dos-Santos, 2015). The counts of the annual growth increments were performed by two independent and experienced readers, and only otoliths with 100% agreement were used (Moura et al., 2020). Considering all four lagoon systems, 3-year-old fish were the most representative in the sampling realized at the capture sites and with the fishnet mesh sizes used, therefore this was the age group selected to perform the analyses. It means that for this study, individuals selected from each site for further analyses were almost juveniles of age group 3⁺ [TL < 46.8 cm, total length at first maturity (Medeiros et al.,

Table 2

Geographic location, sample size (N), and total length (TL) [mean ± standard errors (SE), and range] of *Centropomus undecimalis* individuals collected in the four lagoon systems of Eastern Rio de Janeiro, Brazil. Values are presented as means, standard errors (SE) and ranges.

Lagoon system	Location	n	Date of collection	Mean ± SE	Range
Itaipu	22°96'S;43°04'W	1	Nov. 2019	37.1 ± 1.6	25.1–47.1
		5	Dec. 2019		
		9	Mar. 2020		
Maricá	22°95'S;42°69'W	6	Nov. 2019	37.7 ± 1.5	27.8–46.9
		3	Dec. 2019		
		1	Jan. 2020		
		3	Feb. 2020		
Saquarema	22°93'S;42°49'W	2	Mar. 2020		32.1–43.9
		3	Nov. 2019	38.1 ± 0.8	
		1	Dec. 2019		
		5	Jan. 2020		
Araruama	22°86'S;42°01'W	6	Mar. 2020		24.3–40.2
		3	Nov. 2019	31 ± 1.1	
		5	Feb. 2020		
		7	Mar. 2020		

2021)].

2.3. Otolith microchemistry

Right sagittal otoliths were cleaned (removal of organic tissues), rinsed with ultrapure water, air-dried and mounted in epoxy resin (Buehler, Epothin). Thereafter, they were sectioned preserving the core region using a low-speed diamond saw (Buehler, IsoMet) at 600 rpm, lubricated with ultrapure water (18.2 MΩ cm at 25 °C). The thin slices were grounded with 1200, 2400 and 4000-grade silicon carbide papers (Buehler Ø 200 mm SiC Paper) until the core became visible. Regular optical inspections were done under a metallographic microscope (ML7100, Meiji). Finally, samples were polished using 6, 3, 1 and 0.25 μm diamond pastes (Buehler, Metadi II). The polished sections (~0.6 mm) were fixed on microscope slides with a drop of epoxy resin, and once dried, sonicated for 3 min in ultrapure water (18.2 MΩ cm at 25 °C), and dried in a laminar flow cabinet (Correia et al., 2012).

Trace element analyses were carried out with a NWR Femto femto-second laser model (Elemental Scientific Lasers) coupled to an ICP-QMS Agilent Technologies Model 7700x (Santa Clara, USA). A laser spot diameter of approximately 55 μm was used, with a repetition rate of 50 Hz and a fluence of ~2.5 J cm². This laser spot size allows an adequate balance between the ablated material - resulting signal and the spatial resolution (Soeth et al., 2020; Schroeder et al. 2023; Ferreira et al., 2023). Helium was used as the carrier gas (flow: 600 ml/min) in the laser ablation cell and argon was added before entering the ICP, which was operated at a power of 1600 W. NIST 610 and 612 (trace elements in glass, National Institute of Standards and Technology, USA) and MACS-3 (trace elements in synthetic calcium carbonate, Geology, Geophysics, and Geochemistry Science Center, USA) reference materials, analysed in triplicate at the beginning and at the end of the each session, were used as primary and secondary standards, respectively (Pearce et al., 1997). The ²³⁸U/²³²Th (average 0.96%) and ²³²Th/¹⁶O/²³²Th (average 0.26%) ratios in NIST 612 were used for monitoring the plasma robustness.

A single ablation at the otolith core and edge, with three analytical replicates, was made on sagittal otoliths. The overall laser beam diameter resulting from the replicates sum should represent about 1 month of life for this species (Tucker et al., 1986). Otolith surface was pre-ablated before data acquisition to remove any residual surface contamination. Ion signals from the following isotopes were measured: ¹³⁸Ba, ⁴³Ca (as internal standard: 38.8 wt% in the otoliths, Yoshinaga et al., 2000), ¹¹¹Cd, ⁵⁹Co, ⁶⁵Cu, ⁷Li, ²⁴Mg, ⁵⁵Mn, ⁶⁰Ni, ²⁰⁸Pb, ⁸⁸Sr and ⁶⁶Zn. However, ion signals from ¹¹¹Cd and ²⁰⁸Pb were consistently below the detection limits, and consequently were removed for further statistical analyses. Background ion signals at the different mass to charge ratios were measured at the beginning of each analysis. Standard deviation of background signals was employed in the calculation of detection limits. Detection limits are also dependent on the amount of material ablated and were adjusted for each ablation based on ablation yield estimates (Lahaye et al., 1997). Precision and accuracy were estimated daily for NIST 610, NIST 612 and MACS-3. Precision (relative standard deviation) for the individual elements in the three standards were < 10% (¹³⁸Ba = 6.94%, ⁵⁹Co = 3.45%, ⁶⁵Cu = 7.54%, ⁷Li = 5.29%, ²⁴Mg = 3.89%, ⁵⁵Mn = 2.27%, ⁶⁰Ni = 3.82%, ⁸⁸Sr = 6.56%, and ⁶⁶Zn = 8.34%), while accuracy (recovery rates) estimates based on NIST 610 and MACS-3 range from 101% to 120% (¹³⁸Ba = 111%, ⁵⁹Co = 113%, ⁶⁵Cu = 111%, ⁷Li = 120%, ²⁴Mg = 102%, ⁵⁵Mn = 103%, ⁶⁰Ni = 110%, ⁸⁸Sr = 101%, and ⁶⁶Zn = 105%). Raw data (counts/s) were converted to elemental concentrations rationed to calcium (element/Ca) and presented as molar ratios (mmol element/mol Ca for Sr and μmol element/mol Ca for the other elements). The data reduction process was performed with the lolite package (Paton et al., 2011).

2.4. Statistical analysis

Otolith concentrations were checked for normality, homogeneity of variance and the presence of outliers (Grubb's test) (Correia et al., 2021), but no elemental ratios fulfilled the assumptions simultaneously even after being $\log(x+1)$ transformed. Non-parametric statistics were then used. The data from the core and edge samples were treated separately. Spatial differences in individual fingerprints were explored among sites by permutational univariate analysis of variance (PERANOVA). Pairwise PERANOVAs were used, if needed ($p < 0.05$), to detect differences between sites. Permutational multivariate analysis of variance (PERMANOVA), based on the Mahalanobis distance (9999 permutations), was employed to test multi-elemental differences in otolith core and edge fingerprints among sites. Pairwise PERMANOVAs were used to verify differences in otolith core and edge fingerprints between sites. The reclassification success of fish to their original location taking into account the MES from core and edge were analysed by a flexible discriminant analysis (FDA) (Gareth et al., 2014; Kassambara, 2017; Shroeder et al., 2022). FDA uses nonlinear combination of predictors, such as splines, being useful for modelling multivariate non normality or non-linear relationships between variables within each group, contributing for a more accurate reclassification and better fit than the linear and quadratic discriminant function analyses (Kassambara, 2017; Shroeder et al., 2022). The chemical composition of otolith core corresponds to the early stage of life and may not be related to the capture area, therefore a Ward's hierarchical clustering analysis without prior classification was employed to explore similarity among samples,

where the number of clusters was evaluated by visual inspection of the dendrograms (Tanner et al., 2012; Avigliano et al., 2020; Moreira et al., 2022). The cophenetic correlation coefficient (CCC) was employed to evaluate the match between the dendrograms and the proximity matrix, whose value is considered optimal when exceeds 0.8 (Rohlf, 1970). Nonmetric multidimensional scaling (nMDS), based in Euclidean distances, was used to evaluate graphically the core element similarities (Tanner et al., 2012; Avigliano et al., 2020; Moreira et al., 2022). The goodness-of-fit was estimate using the stress value, which optimal value is below 0.1 (Kruskal, 1964). Mann-Whitney U-tests were used to detect differences between cores and edges fingerprints within each site (Avigliano et al., 2020). Statistical analyses were performed using the vegan (Oksanen et al., 2021), mda (Leisch et al., 2009) and exchange packages in the R programming environment (R Development Core Team, 2022). Results are presented as mean \pm standard errors. A significance level of $p < 0.05$ was adopted.

3. Results

3.1. Otolith core elemental analysis

3.1.1. Single elemental analysis

The Ba/Ca, Li/Ca, and Sr/Ca ratios showed differences among sites in otolith cores (PERANOVAs; $p < 0.05$) (Table 3). The Ba/Ca ratio (overall range: 0.067 – 8.590 $\mu\text{mol/mol}$) differed between Itaipu and Maricá, Itaipu and Araruama, and Maricá and Saquarema (pairwise PERANOVAs; $p < 0.05$; Fig. 2). The Li/Ca ratio (overall range: 1.691 –

Table 3

Comparison of *Centropomus undecimalis* element/Ca core and edge ratios among locations using a PERANOVA. Significant statistical differences ($p < 0.05$) were marked in bold. DF = degrees of freedom, SS = sums of squares.

		Ba/Ca				Co/Ca			
Section	Source	DF	SS	pseudo-F	p	DF	SS	pseudo-F	p
Core	Location	3	1.06E-05	5.23	0.0030	3	1.32E-08	1.12	0.3502
	Residual	56	3.77E-05			56	2.19E-07		
	Total	59				59			
Edge	Location	3	8.60E-06	9.55	0.0001	3	1.47E-08	1.22	0.3209
	Residual	56	1.68E-05			56	2.25E-07		
	Total	59				59			
		Cu/Ca				Li/Ca			
Section	Source	DF	SS	pseudo-F	p	DF	SS	pseudo-F	p
Core	Location	3	4.97E-08	1.52	0.2200	3	4.45E-06	5.18	0.0028
	Residual	56	6.11E-07			56	1.61E-05		
	Total	59				59			
Edge	Location	3	2.18E-08	0.76	0.5278	3	1.05E-05	11.80	0.0001
	Residual	56	5.38E-07			56	1.67E-05		
	Total	59				59			
		Mg/Ca				Mn/Ca			
Section	Source	DF	SS	pseudo-F	p	DF	SS	pseudo-F	p
Core	Location	3	1.75E-03	1.75	0.1661	3	7.10E-06	1.05	0.3738
	Residual	56	1.87E-02			56	1.26E-04		
	Total	59				59			
Edge	Location	3	2.12E-03	1.09	0.3574	3	4.42E-05	7.77	0.0003
	Residual	56	3.63E-02			56	1.06E-04		
	Total	59				59			
		Ni/Ca				Sr/Ca			
Section	Source	DF	SS	pseudo-F	p	DF	SS	pseudo-F	p
Core	Location	3	1.99E-08	1.39	0.2448	3	9.44E-03	3.58	0.0214
	Residual	56	2.67E-07			56	4.92E-02		
	Total	59				59			
Edge	Location	3	9.01E-09	0.62	0.5969	3	1.71E-02	3.47	0.0216
	Residual	56	2.70E-07			56	9.16E-02		
	Total	59				59			
		Zn/Ca							
Section	Source	DF	SS	pseudo-F	p	DF	SS	pseudo-F	p
Core	Location	3	1.19E-08	0.74	0.5282	3	9.44E-03	3.58	0.0214
	Residual	56	2.98E-07			56	4.92E-02		
	Total	59				59			
Edge	Location	3	2.94E-09	0.17	0.9150	3	1.71E-02	3.47	0.0216
	Residual	56	3.18E-07			56	9.16E-02		
	Total	59				59			

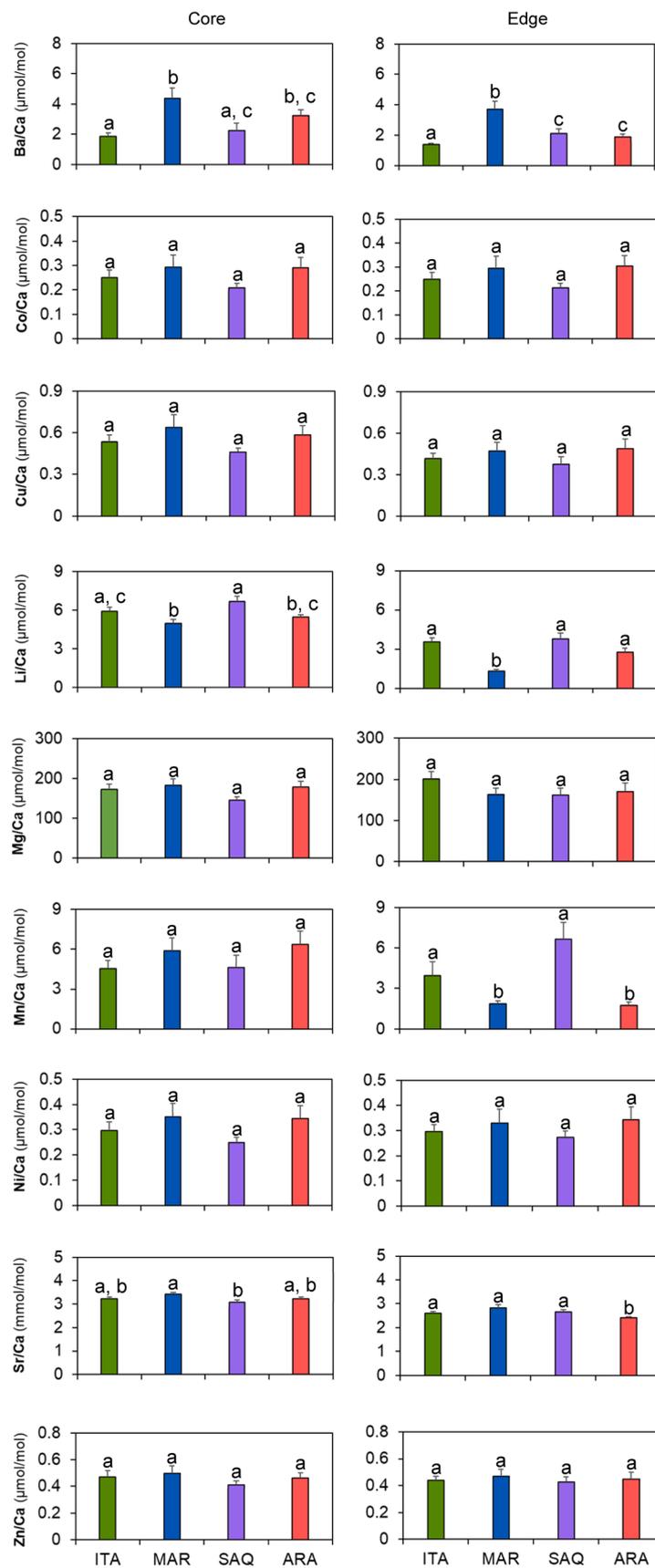


Fig. 2. Element/Ca ratios in otolith cores and edges of *Centropomus undecimalis* collected in the lagoons systems of eastern Rio de Janeiro, Brazil. Different letters above the columns indicate significant statistical differences observed between locations (pairwise PERANOVA: $p < 0.05$). Elemental concentrations (detrended concentrations for all ratios) are showed as mean values \pm standard errors. ITA = Itaipu, MAR = Maricá, SAQ = Saquarema, ARA = Araruama.

8.575 $\mu\text{mol/mol}$) differed significantly between Itaipu and Maricá, Maricá and Saquarema, and Saquarema and Araruama (pairwise PERANOVAs; $p < 0.05$; Fig. 2). The Sr/Ca ratio (overall range: 2.666 – 4.129 mmol/mol) differed significantly between Maricá and Saquarema (pairwise PERANOVAs; $p < 0.05$; Fig. 2). However, the Co/Ca (overall range: 0.105 – 0.658 $\mu\text{mol/mol}$), Cu/Ca (overall range: 0.244 – 1.304 $\mu\text{mol/mol}$), Mg/Ca (overall range: 98.536 – 311.947 $\mu\text{mol/mol}$), Mn/Ca (overall range: 1.392 – 13.777 $\mu\text{mol/mol}$), Ni/Ca (overall range: 0.103 – 0.750 $\mu\text{mol/mol}$) and Zn/Ca (overall range: 0.167 – 0.834 $\mu\text{mol/mol}$) (Fig. 2) ratios did not show any significant differences among locations (PERANOVAs; $p > 0.05$) (Table 3).

3.1.2. Multi-elemental analysis

Significant differences among the lagoon systems for the otolith core MES were found in the overall PERMANOVA (pseudo-F = 1.9116; $df = 3$; $p < 0.05$) (Table 4). In the pairwise comparisons, the Maricá lagoon system differed from the Saquarema (axis 1) and Itaipu from Marica (axis 2) (pairwise PERMANOVAs; $p < 0.05$) (Table 4). The FDA using the otolith core MES, showed a partial overlap among Itaipu (green), Saquarema (our+le) and Araruama (red) in comparison to the Maricá lagoon system (Fig. 3). The values of the reclassification matrix showed an overall reclassification of 45% for the individuals to their original lagoon systems (53% Saquarema, 53% Maricá, 47% Itaipu and 27% Araruama) (Table 5). The Ward's hierarchical clustering analysis using the otolith core MES produced three main clusters with 13, 29 and 18 samples, respectively (Fig. 4), with a moderate CCC (0.62) and an apparent clustering between individuals from Saquarema (cluster 1) and Maricá (cluster 3). With a stress value of 0.001, the nMDS corroborated the separation suggested in the cluster analysis, supporting the discrimination between Maricá and Saquarema along coordinate 1. The Ward's hierarchical clustering analysis using otolith edge MES produced three main clusters with 21, 14 and 25 samples, respectively (Fig. 5). These clusters exhibited a moderate CCC (0.58), and there was an apparent clustering between individuals from Araruama (cluster 1) and Maricá (cluster 3), with the latter not being as robust. With a stress value of 0.002, the nMDS showed a good clustering ability, supporting the discrimination between them along coordinate 1.

3.2. Otolith edge elemental analysis

3.2.1. Single elemental analysis

The otolith edges showed differences among sites for Ba/Ca, Li/Ca, Mn/Ca and Sr/Ca ratios (PERANOVAs; $p < 0.05$) (Table 3). The Ba/Ca ratio (overall range: 0.798 – 6.978 $\mu\text{mol/mol}$) was higher in Maricá, lower in Itaipu and intermediary in Saquarema and Araruama (pairwise PERANOVAs; $p < 0.05$; Fig. 2). The Li/Ca ratio (overall range: 0.342 – 6.934 $\mu\text{mol/mol}$) was lower in Maricá compared to the other lagoon systems (pairwise PERANOVAs; $p < 0.05$; Fig. 2). The Mn/Ca ratio (overall range: 0.517 – 14.447 $\mu\text{mol/mol}$) was higher in Itaipu and Saquarema, and lower in Maricá and Araruama (pairwise PERANOVAs; $p < 0.05$; Fig. 2). The Sr/Ca ratio (overall range: 2.0006 – 3.6664 mmol/mol) was lower in Araruama compared to the other lagoon systems

(pairwise PERANOVAs; $p < 0.05$; Fig. 2). However, the Co/Ca (overall range: 0.120 – 0.699 $\mu\text{mol/mol}$), Cu/Ca (overall range: 0.167 – 1.033 $\mu\text{mol/mol}$), Mg/Ca (overall range: 75.454 – 315.242 $\mu\text{mol/mol}$), Ni/Ca (overall range: 0.1254 – 0.7052 $\mu\text{mol/mol}$) and Zn/Ca (overall range: 0.181 – 0.822 $\mu\text{mol/mol}$) (Fig. 2) ratios did not show any significant differences among locations (PERANOVAs; $p > 0.05$) (Table 3).

3.2.2. Multi-elemental analysis

The otolith edge MES showed significant differences among the lagoon systems in the overall PERMANOVA (pseudo-F = 3.9953; $df = 3$; $p < 0.05$) (Table 4). In the pairwise comparisons, were founded statistically differences between all the lagoon systems (pairwise PERMANOVAs; $p < 0.05$) (Table 4). For the edges, a spatial separation among the four systems was observed in the FDA (Fig. 3), with minimal overlapping of points. Axis 1 separated Saquarema from Araruama, while axis 2 separated Itaipu from Maricá. The values of the reclassification matrix showed an overall reclassification of 65% for the individuals to their original lagoon systems (73% Itaipu, 73% Saquarema, 60% Maricá, and 53% Araruama) (Table 5).

3.3. Comparison between otolith core and edge elemental analysis

The Ba/Ca, Cu/Ca, Li/Ca, Mn/Ca and Sr/Ca ratios showed differences between cores and edges (Mann-Whitney *U*-test; $p < 0.05$) within sites (Table 6). The Ba/Ca ratio was higher in the cores in Araruama (Mann-Whitney *U*-test; $p < 0.05$) (Fig. 2). The Cu/Ca ratio was higher in the cores in Saquarema (Mann-Whitney *U*-test; $p < 0.05$) (Fig. 2). The Li/Ca ratios were higher in the cores than edges in the four lagoon systems (Mann-Whitney *U*-test; $p < 0.05$) (Fig. 2). The Mn/Ca was higher in the core in Maricá and Araruama (Mann-Whitney *U*-test; $p < 0.05$) (Fig. 2). The Sr/Ca ratios were higher in the cores than edges in the four lagoon systems (Mann-Whitney *U*-test; $p < 0.05$) (Fig. 2).

4. Discussion

The results obtained through the otolith multi-elemental signatures of the core of *C. undecimalis* 3-year-old juvenile individuals suggest a natal origin with similar characteristics, i.e., in an exclusively marine environment or under strong marine influence, such as the connecting channels between lagoons and the sea. This finding corroborates the hypothesis proposed by Ley et al. (2010), who observed the formation of reproductive aggregates of females in salinities greater than 28 to release eggs. These eggs hatch one day after fertilization, and the larvae, for approximately 15 days, develop in the water column, moving with the currents of the spawning sites. Later, they look for a nursery area. Furthermore, our results showed high plasticity in the use of habitats, i.e., lagoon systems with different physical-chemical attributes. The dataset regarding the capture areas (edges) evidenced a microchemical distinction of the water bodies among the lagoons. These natural tags suggest the utilization of habitats with distinct physicochemical characteristics by a species with transient estuarine habits, proving its ecological plasticity. This finding partially supports the hypothesis that

Table 4

Overall and pairwise PERMANOVA comparisons among the four lagoon systems regarding the otolith core and edge multielemental signatures. Significant statistical differences ($p < 0.05$) were marked in bold.

Overall PERMANOVA					Pairwise PERMANOVA				
Section	DF	SS	pseudo-F	p	Lagoon system	Itaipu	Maricá	Saquarema	Araruama
Core	3	3.29E+01	1.9116	0.0099	Itaipu		0.0100	0.1690	0.2320
					Maricá	0.0100		0.0070	0.1757
					Saquarema	0.1690	0.0070		0.1486
					Araruama	0.2320	0.1757	0.1486	
Edge	3	6.24E+01	3.9953	0.0001	Itaipu		0.0001	0.0014	0.0052
					Maricá	0.0001		0.0002	0.0176
					Saquarema	0.0014	0.0002		0.0002
					Araruama	0.0052	0.0176	0.0002	

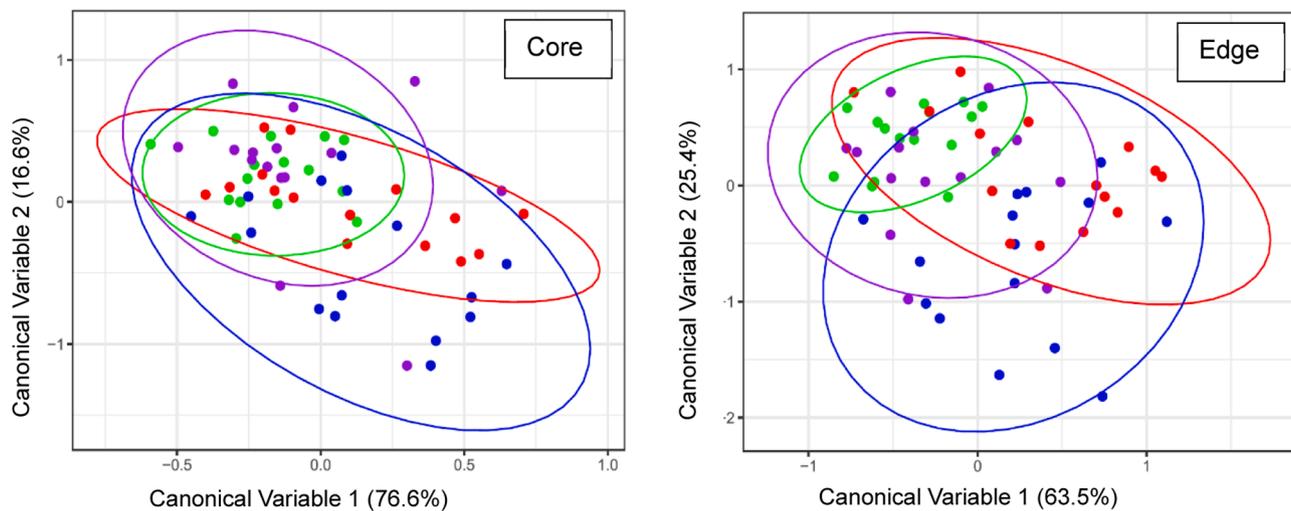


Fig. 3. Flexible discriminant analysis showing spatial differences in the analysis of *Centropomus undecimalis* multielement signatures of otolith cores and edges. Itaipu: green; Maricá: blue; Saquarema: purple and Araruama: red.

Table 5

Reclassification matrix based on FDA values for *Centropomus undecimalis* multielemental signatures of otolith cores and edges in different lagoon systems.

Original locations	Predicted locations				% Correct
	Itaipu	Maricá	Saquarema	Araruama	
Core					
Itaipu	7	1	5	2	47
Maricá	3	8	0	4	53
Saquarema	3	2	8	2	53
Araruama	5	4	2	4	27
Total					45
Edge					
Itaipu	11	1	3	0	73
Maricá	1	9	0	5	60
Saquarema	0	3	11	1	73
Araruama	4	3	0	8	53
Total					65

C. undecimalis use complex habitats, such as the lagoon systems of Eastern Rio de Janeiro, as nurseries and growing areas. They inhabit these ecosystems until reaching sexual maturity (TL > 55 cm; Nascimento et al., 2022), when they leave these ecosystems to constitute the adult stock in rivers, mangroves, or coastal marine waters (Ley et al., 2010; Silva et al., 2019). Otolith elemental signatures of juveniles of *C. undecimalis* carried out in the Northwest Atlantic showed differences between different nursery areas, where fish enter in the initial development stages and remain residents until reaching the sexual maturity (Patterson et al., 2005; Ley et al., 2010; Ley and Rolls, 2018). Studies performed for other estuarine and marine coastal fishes in the southwest Atlantic using analyses of elemental signatures from otolith cores and edges have been useful to infer about the population structure and ontogenetic changes in fish habitats (Franco et al., 2019; Soeth et al., 2020; Maciel et al., 2021).

The variations found in the elemental concentrations of the cores and edges of the otoliths are due to the chemical concentrations of the elements in the water of the different environments that *C. undecimalis* inhabits throughout its ontogenetic development, as well as due to physiological processes related to growing, feeding, metabolism and energetic cost (Thomas et al., 2017; Ley and Rolls, 2018; Izzo et al., 2018). The results of the analyses of *C. undecimalis* otolith's core and edge elemental signatures among lagoon systems indicate that differences were mainly found in the element/Ca ratios related to environmental concentrations (e.g. Sr/Ca, Ba/Ca, Mn/Ca and Li/Ca) (Barnes and Gillanders, 2013; Walsh and Gillanders, 2018; Reis-Santos et al.,

2022), as opposed to those under strong physiological regulation (e.g. Co/Ca, Cu/Ca, Mg/Ca and Zn/Ca) (Hüssy et al., 2021), that showed no differences hereby. Sr, Ba, Mn and Li present highly accurate responses in estuarine and coastal environments under strong marine (Sr and Li) or continental (Mn and Ba) influences, whose incorporation into otoliths may occur by randomly trapping in the interstitial spaces of the aragonite matrix, or by interacting with the same protein complexes than Ca (Izzo et al., 2018; Thomas et al., 2017; Walther, 2019). The Co, Cu, Mg and Zn are more related to the regulatory processes related to the physiology of the fish due to their roles as biomolecular co-factors and cellular processes, and may present variations due to metabolic processes, growth rates and feeding regimes (Sturrock et al., 2015; Thomas et al., 2017; Hüssy et al., 2021). The *C. undecimalis* is a resilient fish to significant environmental changes in the physical-chemical parameters during its migratory life cycle, which contributes to the lack of differences among lagoon systems in terms of physiologically regulated elements (Ley et al., 2010). Ba is strongly correlated with continental contribution, whose high concentrations indicate a greater freshwater contribution to the lagoon system and less exchange with the marine environment (Webb et al., 2012; Santana et al., 2018; Moreira et al., 2022). These results may indicate some environmental influence of the lagoon systems in the otolith core signatures, that could represent the nursery grounds and the migration of the juveniles to the growth area (Correia et al., 2012; Gibb et al., 2016; Moreira et al., 2022). The Maricá lagoon system is the environment with less water exchange with the sea, while Itaipu presents daily renewal of its waters, affecting the Ba incorporation by *C. undecimalis* (Albuquerque et al., 2010; Dias et al., 2021). However, high concentrations of Ba can also indicate contamination by pollutants (Gomes et al., 2017; Daros et al., 2022), such as in Itaipu under strong urban pressure (Fontenelle e Corrêa, 2014), contribution by underground aquifers (Shaw et al., 1998), such as in Maricá (Cristo et al., 2015), or by coastal upwelling (Elsdon et al., 2008; Woodson et al., 2013; Artetxe-Arrate et al., 2019). The Ba/Ca ratios showed higher concentrations in the otolith cores than on the edges in *C. undecimalis* collected in the Araruama lagoon system, an ontogenetic variation that may indicate that 0⁺ individuals from the coastal zone could be exposed to high concentrations of Ba caused by the coastal upwelling of South Atlantic Central Water (SACW) that occurs in the eastern region of Rio de Janeiro (Castro et al., 2006; Madureira et al., 2020; Corrêa et al., 2022) before entering in the lagoons system. Elevated concentrations of Ba in otoliths of sea-caught fish have been reported for *Chaetopterus faber* in the southwest Atlantic, an environment subject to SACW upwelling events (Soeth et al., 2020). Co is an element whose concentrations in fish otoliths are related to

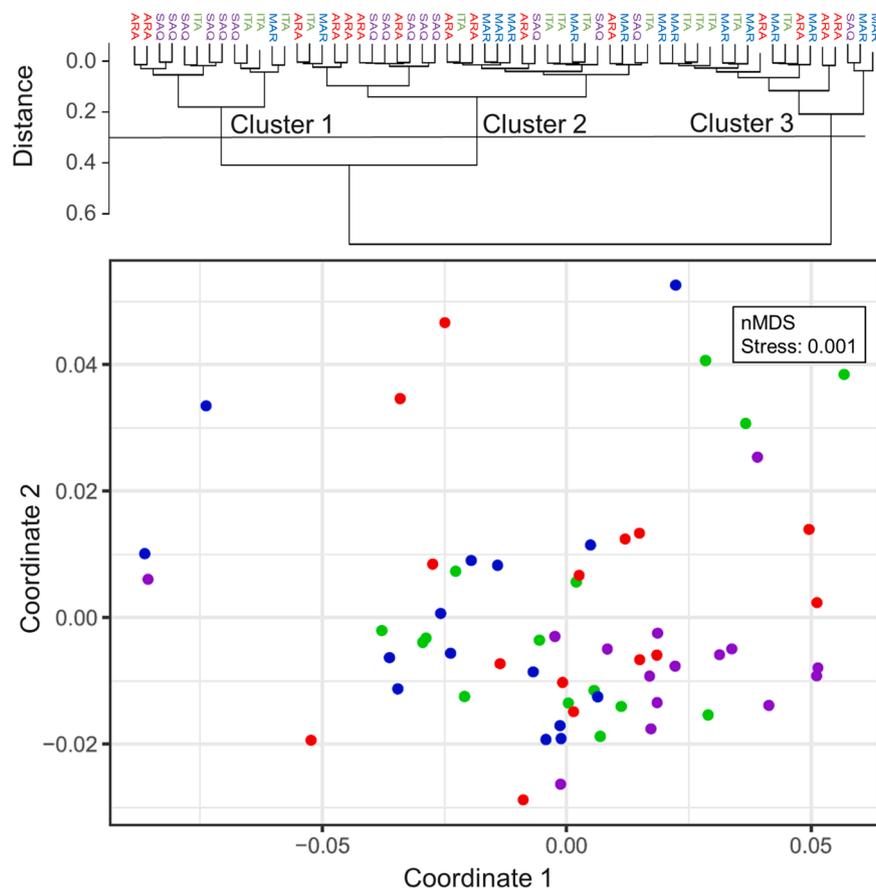


Fig. 4. Ward's hierarchical clustering dendrogram and nonmetric Multidimensional Scaling (nMDS) based on otolith core chemical composition. Itaipu: green; Maricá: blue; Saquarema: purple and Araruama: red.

physiological factors (Thomas et al., 2017). However, no differences were found in the Co/Ca ratios among lagoon systems, as well as between otolith cores and edges, demonstrating that the concentrations of the element in *C. undecimalis* show some stability between different environments, as well as ontogenetically. The Cu is an element that can be physiologically regulated in fish, however high environmental concentrations can affect Cu/Ca ratios in otoliths (Correia et al., 2012; Sturrock et al., 2015). The Cu/Ca ratios did not show differences among lagoon systems, however the otolith cores from individuals collected in Saquarema showed higher concentrations than the edges. Environmental temperature and fish condition of the individuals are some of the factors that influence Cu concentrations in fish otolith, factors subject to variation with the ontogenetic development and habitat shift of *C. undecimalis* (Sturrock et al., 2015). Li is an element whose concentrations in otoliths are related to environmental concentrations, being correlated to high salinity waters (Hicks et al., 2010). The Li/Ca ratios showed lower concentrations in otolith cores and edges from *C. undecimalis* collected in Maricá and Araruama lagoon systems, environments with longer residence times of their waters and lower exchanges with the sea (Dias et al., 2021). The otolith cores from *C. undecimalis* collected in all lagoon systems showed higher concentrations in Li/Ca ratios than edges, suggesting that the spawning grounds where *C. undecimalis* individuals originated have higher salinity than the nursery habitats of 3⁺ individuals. Mg is an element whose concentrations in otoliths are related to physiological factors (Woodcock et al., 2012). However, differences were not founded in Mg/Ca ratios among otolith from individuals collected in the lagoon systems, such as between otolith cores and edges, probably because of the migratory behaviour of *C. undecimalis* and their environmental resilience to physiological effects (Nunes et al., 2018). Mn is an element whose

concentrations in otoliths are related to environmental contribution (Elsdon et al., 2008; Laugier et al., 2015), including hypoxic conditions (Limburg et al., 2015), parental transfer (Thomas et al., 2020) and physiological regulation (Elsdon and Gillanders, 2003). Despite the absence of differences in Mn/Ca ratios among otolith cores from *C. undecimalis* collected in the four lagoon systems, Saquarema and Itaipu had the highest concentrations at the edges, while Maricá and Araruama had the lowest concentrations. Itaipu and Saquarema have large vegetated areas with swamps and mangroves in their innermost zones, anoxic environments capable of contributing with a high amount of organic matter and fine sediment in suspension, allowing greater bioavailability of Mn in the water column (Lacerda et al., 1999; Lenz et al., 2015; Reis-Santos et al., 2022). Ontogenetic variations in Mn/Ca concentrations between otolith cores and edges were detected, with Maricá and Araruama showing large reductions in concentrations at the edges when compared to the cores. The Mn is an element that concentrations in otoliths can be affected by parental transfer, justifying the higher concentrations in the cores than edges in Maricá and Araruama (Correia et al., 2011; Correia et al., 2012; Thomas et al., 2020). Furthermore, the Maricá and Araruama lagoon systems do not present relatively large mesohabitats areas with mangroves or swamps that can contribute with high amounts of Mn, justifying the low incorporation of this element in the otolith edges of 3⁺ individuals of *C. undecimalis* in these sites (Lacerda et al., 1999; Lenz et al., 2015; Reis-Santos et al., 2022). Ni is an element whose concentrations in otoliths come from environmental contribution, which may indicate anthropic impacts such as the release of mining residues and urban-industrial contaminants (Friedrich and Halden, 2010). However, the Ni/Ca ratios showed no differences among samples collected in the lagoon systems, nor between the cores and edges of the otoliths. Sr is an element whose incorporation

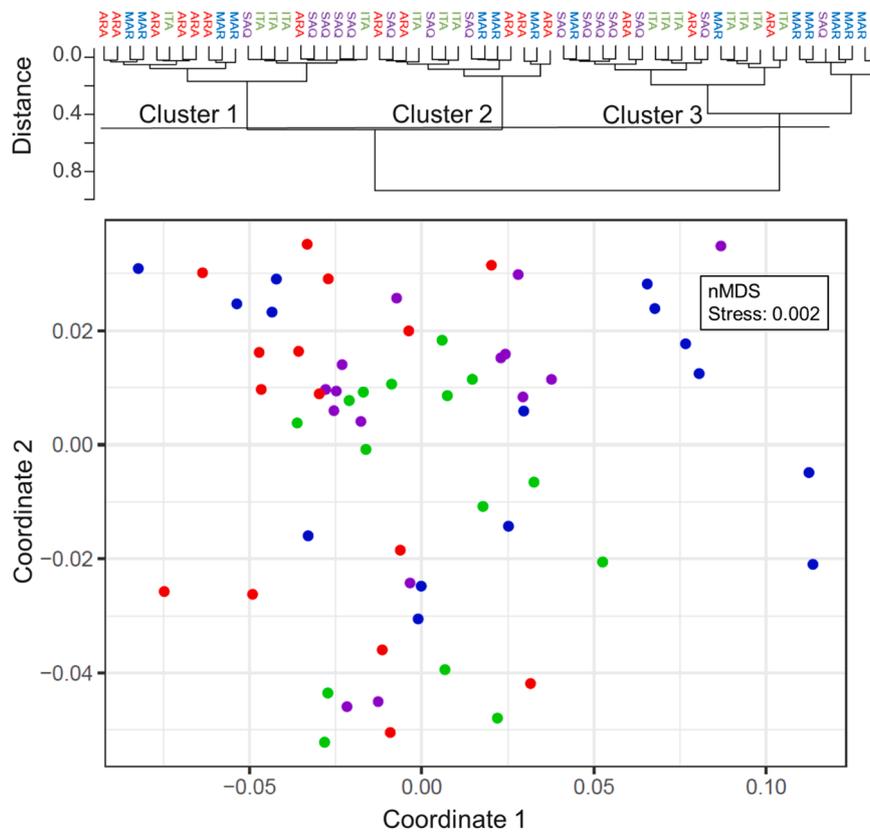


Fig. 5. Ward's hierarchical clustering dendrogram and nonmetric Multidimensional Scaling (nMDS) based on otolith edge chemical composition. Itaipu: green; Maricá: blue; Saquarema: purple and Araruama: red.

Table 6

Pairwise comparison of *Centropomus undecimalis* element/Ca ratios between otolith sections (core and edge) using Mann-Whitney U-tests. Significant statistical differences ($p < 0.05$) were marked in bold.

Element ratio	Lagoon system							
	Itaipu		Maricá		Saquarema		Araruama	
	U	p	U	p	U	p	U	p
Ba/Ca	147	0.1607	126	0.5894	97	0.5393	183	0.0027
Co/Ca	101	0.6529	119	0.8195	110	0.9349	107	0.8381
Cu/Ca	159	0.0555	154	0.0892	168	0.0209	148	0.1485
Li/Ca	206	0.0001	220	0.0001	202	0.0001	215	0.0001
Mg/Ca	87	0.3046	133	0.4124	97	0.5393	135	0.3669
Mn/Ca	143	0.2169	194	0.0004	85	0.2625	206	0.0001
Ni/Ca	107	0.8381	132	0.4363	102	0.6827	108	0.8702
Sr/Ca	214	0.0001	179	0.0062	196	0.0003	221	0.0001
Zn/Ca	124	0.6529	119	0.8034	107	0.8381	129	0.5125

into otoliths is subject to environmental concentrations, being highly correlated with salinity (Elsdon and Gillanders, 2004; Webb et al., 2012; Daros et al., 2016). Among the samples collected in the lagoon systems, Saquarema had the lowest concentrations of Sr/Ca for the otolith cores, while Araruama had the lowest concentrations for the edges. Low Sr/Ca values were not expected to occur in Araruama because it is a hypersaline lagoon system; however it is a heterogeneous environment that contains several areas of high continental freshwater runoff contribution and low salinity places where 3^+ individuals of *C. undecimalis* prefer to remain (Bertucci et al., 2016). When comparing cores and edges, Sr/Ca concentrations were higher in cores for all lagoon systems, indicating that 0^+ individuals of *C. undecimalis* come from areas of higher salinity than areas where 3^+ individuals remain (Daros et al., 2016). Zn is an element whose concentrations in otoliths are due to physiological factors or food intake (Halden et al., 2000; Ranaldi and Gagnon, 2008; Thomas et al., 2017). The absence of differences among the Zn/Ca

concentrations in otoliths collected in the lagoon systems, such as between cores and edges reinforces the physiological resilience of *C. undecimalis* to environmental and diet variations (Thomas et al., 2017; Pereira et al., 2015). In these lagoon systems, their main preys are shrimps, small fish, and small crabs (Almeida et al., 2021).

The otolith core MES reached a low overall (45%) and specific (53% Saquarema, 53% Maricá, 47% Itaipu and 27% Araruama) reclassifications. Moreover, a high overlap among the different lagoon systems in the FDA for the otolith core MES demonstrated that individuals were originated in sites with similar environmental characteristics. The pairwise PERMANOVAs values for the otolith core MES showed differences between lagoon systems with more environmental dissimilarities (Itaipu and Maricá, Maricá and Saquarema), independently of the distance between the sites. Spawning aggregations of *C. undecimalis* occur in different types of coastal environments, usually characterized by high salinity, such as bay channels, river mouths, beaches, rocky reefs and

coastal islands (Adams et al., 2009; Ley et al., 2010; Young et al., 2014; Danta and Barletta, 2016). This ecological trait could influence the chemical composition of the otoliths of 0^+ individuals by increasing the concentration of elements related to high salinities (Ley et al., 2010; Daros et al., 2016; Ley and Rolls, 2018). However, the clustering between individuals from Saquarema and Maricá, and the high stress value of the nMDS for otolith core MES indicate that the chemical composition was influenced in distinct manner, probably associated to entrance of the *C. undecimalis* eggs, larvae, and juveniles in these lagoon systems. However, the otolith edge MES reached a higher overall (65%) and specific (73% Itaipu, 73% Saquarema, 60% Maricá, and 53% Araruama) reclassifications. Additionally, differences in the main and pairwise PERMANOVAs between all lagoon systems for the otolith edges MES demonstrate that 3^+ individuals constitute heterogeneous groups with distinct phenotypic characteristics. Concerning the FDA for otolith edges MES, there were higher discrimination rates for the lagoon systems of Itaipu and Saquarema, the environments studied with the larger abundance of vegetation in their marginal areas and the greatest renewal rates of their waters (Costa et al., 2021). Regarding the otolith edge MES, the lowest reclassification rates were founded in Maricá and Araruama lagoon systems, the environments with the longest water residence times and that suffer more anthropic influences in their marginal areas (Silva et al., 2016; Dias et al., 2021; Costa et al., 2021). The Maricá lagoon system is a hypereutrophic ecosystem that presents a limited water exchange in their inner zone because of the narrow channels, eventually requiring sandbar openings for sea water incoming (Mansur et al., 2012; Silva and Molisani, 2019; Dias et al., 2021). The Araruama lagoon system is a hypersaline ecosystem that has been suffering numerous anthropic impacts, such as the removal of native marginal vegetation, construction of salt flats, limestone extraction and emissions of urban-industrial effluents that have been affecting the salinity, primary productivity, organic matter and pollutants input in the ecosystem (Souza et al., 2003; Mansur et al., 2012; Dias et al., 2021).

Despite having a pattern of habitat use throughout the different stages of the life cycle, variations can occur in different populations of *C. undecimalis*, indicating that the species can adapt to different habitat conditions, such as types of vegetation, transitional environments and nature of tidal channels (Ray, 2005; Ley et al., 2010; Brame et al., 2014). Differences found between the elemental signatures in the otolith cores and edges indicate that the *C. undecimalis* presents ontogenetic shifts in habitat use, with differences indicating a major influence of coastal marine waters in the 0^+ stage and a segregation among lagoon systems in the 3^+ stage, driven by environmental local characteristics. In the elemental signatures of *C. undecimalis* otolith edges, the lagoon systems of Itaipu and Saquarema showed distinct patterns from Maricá and Araruama, indicating that the particular characteristics of these ecosystems influence the life history of the species. The lagoon systems of Itaipu and Saquarema have shorter water residence times, in addition to preserved and vegetated marginal areas, allowing greater connectivity of ecosystems with the sea, as well as large availability of shelter for juveniles of *C. undecimalis* (Almeida et al., 2021; Costa et al., 2021; Dias et al., 2021). However, the Maricá and Araruama lagoon systems have longer water residence times and more impacted margins by urbanization and enterprises, therefore presenting limitations regarding the connectivity of these ecosystems with the sea, as well as less availability of shelter for juveniles of *C. undecimalis* (Silva and Rosman, 2016; Costa et al., 2021; Dias et al., 2021).

Fish populations that migrate among different environments throughout their life history stages impose numerous challenges for fisheries management, such as the delimitation of fish stocks, identification of areas of reproductive aggregation, and nursery and recruitment grounds (Ray, 2005; Adams et al., 2009; Lowerre-Barbieri et al., 2014). There are some attributes that can indicate the importance of nursery grounds, as the connectivity to adult habitats, abundance of recruits and higher survival rates (Chitarro et al., 2009). The ability to move among marine, estuarine and freshwater environments has given

C. undecimalis with evolutionary advantages; however intense fishing exploitation may threaten the maintenance of the species' stocks when it acts on certain population strata of the species (Ley et al., 2010; Young et al., 2014; Tubino et al., 2021). Anthropogenic interventions in the estuarine and coastal ecosystems such as vegetation removal, shoreline urbanization, effluent release, channel openings and obstruction of rivers can affect the connectivity and integrity of the habitats necessary for the recruitment and development of *C. undecimalis*. (Milton, 2009; Mansur et al., 2012; Costa et al., 2021). Changes in water flow due to variations in rainfall patterns and sea level rise due to climate change also impose threats to mesohabitats and nursery areas where *C. undecimalis* juveniles occur (Gerlach et al., 2017; Valle-Levinson et al., 2017; Ley and Rolls, 2018). Thus, an accurate identification of the juvenile residence and connectivity patterns between spawning and nursery grounds is vital in order to contribute to the conservation of the species in environments highly subject to human interventions, such as the lagoon systems of Eastern Rio de Janeiro (Ley et al., 2010; Vasconcelos et al., 2011; Almeida et al., 2021).

The present study suggests a relationship between the elemental signatures of otolith cores and waters with higher marine influence, and discrepancy among otolith edges in different lagoon systems, demonstrating that *C. undecimalis* make an ontogenetic habitat shift between 0^+ and 3^+ stages. This study emphasizes the importance of accurate identification of the connectivity patterns among the habitats where *C. undecimalis* development occurs. Furthermore, the results demonstrate that *C. undecimalis* 3-year-old juveniles are distributed in heterogeneous groups with distinct phenotypic features, associated to environmental characteristics of the lagoon systems of Eastern Rio de Janeiro. The obtained results reinforce the importance of these ecosystems as nurseries, and the need of management measures aimed at conserving habitats and maintaining the link between lagoon systems and marine coastal areas. Further work should focus on identifying stocks, contribution of nurseries and influence of mesohabitat on the ontogenetic development of *C. undecimalis*, in order to implement management strategies for the conservation of the species and ecosystems.

CRediT authorship contribution statement

Rafal Tubino: Writing – review & editing. **Alberto Teodorico Correia:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Jorge Pisonero:** Resources, Formal analysis. **Cassiano Monteiro-Neto:** Writing – review & editing. **Rebeca Dias de Souza Coutinho:** Investigation, Formal analysis. **Ana Méndez-Vicente:** Resources, Formal analysis. **Paulo Roberto Camponez de Almeida:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Marcus Rodrigues da Costa:** Writing – review & editing, Supervision, Project administration, Conceptualization.

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.

Data Availability

Data will be made available on request.

Acknowledgements

The present study is part of the project "Pesquisa Marinha e Pesqueira," which is an offset measure established under a consent decree between the company PRIO and the Federal Public Prosecutors' Office in Rio de Janeiro. The project was funded by the Brazilian Fund for

Biodiversity (FUNBIO). The authors thank the financial support provided by the Coordination for the Improvement of Higher Education Personnel (CAPES) and the Brazilian Fund for Biodiversity (FUNBIO) for the execution of the subproject titled "Sistemas Lagunares do Leste Fluminense- SLLF (short title)" within the framework of the Project "Mecanismos Reguladores da Produção Pesqueira nos Sistemas Lagunares do Leste Fluminense: estado atual e cenários futuros." Additionally, this study received support from international funds through FCT—Foundation for Science and Technology, as part of UIDB/04423/2020 and UIDP/04423/2020.

References

- Able, K.W., 2005. A re-examination of fish estuarine dependence: evidence for connectivity between estuarine and ocean habitats. *Estuar., Coast. Shelf Sci.* 64 (1), 5–17.
- Adams, A., Wolfe, R.K., Barkowski, N., Overcash, D., 2009. Fidelity to spawning grounds by a catadromous fish, *Centropomus undecimalis*. *Mar. Ecol. Prog. Ser.* 389, 213–222.
- Albuquerque, C.Q., Miekeley, N., Muelbert, J.H., 2010. Whitemouth croaker, *Micropogonias furnieri*, trapped in a freshwater coastal lagoon: a natural comparison of freshwater and marine influences on otolith chemistry. *Neotrop. Ichthyol.* 8, 311–320.
- 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., Cadihlo, 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., & R. Angelini (Eds.), *Pesca e sustentabilidade: passado, presente e futuro*. AH Edições. pp. 71–92.
- Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.D.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. *Meteorol. Z.* 22 (6), 711–728.
- 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.
- Avigliano, E., Volpedo, A.V., 2016. A review of the application of otolith microchemistry toward the study of Latin American fishes. *Rev. Fish. Sci. Aquac.* 24 (4), 369–384.
- Avigliano, E., Pisonero, J., Bordel, N., Dománico, A., Volpedo, A.V., 2019. Mixed-stock and discriminant models use for assessing recruitment sources of estuarine fish populations in La Plata Basin (South America). *J. Mar. Biol. Assoc. U. Kingd.* 99 (6), 1429–1433.
- Avigliano, E., Ibañez, A., Fabré, N., Callico Fortunato, R., Méndez, A., Pisonero, J., Volpedo, A.V., 2020. White mullet *Mugil curema* population structure from Mexico and Brazil revealed by otolith chemistry. *J. Fish. Biol.* 97 (4), 1187–1200.
- 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*. FINEP, Niterói, pp. 47–56.
- Barcellini, V.C., Motta, F.S., Martins, A.M., Moro, P.S., 2013. Recreational anglers and fishing guides from an estuarine protected area in southeastern Brazil: Socioeconomic characteristics and views on fisheries management. *Ocean Coast. Manag.* 76, 23–29.
- Barnes, T.C., Gillanders, B.M., 2013. Combined effects of extrinsic and intrinsic factors on otolith chemistry: implications for environmental reconstructions. *Can. J. Fish. Aquat. Sci.* 70 (8), 1159–1166.
- Barroso, L.V., Medina, R.S., Moreira-Turcq, P.F. & Bernardes, M.C. 2000. A pesca nas lagoas costeiras fluminenses. Brasília: Ed. Ibama, 50p.
- Beck, M.W., Heck, K.L., Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Weinstein, M.P., 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *BioScience* 51, 633–641.
- Begossi, A., Salyvonchik, S., Nora, V., Lopes, P.F., Silvano, R.A., 2012. The Paraty artisanal fishery (southeastern Brazilian coast): ethnoecology and management of a social-ecological system (SES). *J. Ethnobiol. Ethnomed.* 8 (1), 1–19.
- Bertucci, T.C.P., Silva, E.P., Marques Jr, A.N., Monteiro Neto, C., 2016. Turismo e urbanização: os problemas ambientais da Lagoa de Araruama-Rio de Janeiro. *Ambient. Soc.* 19, 59–80.
- Brame, A.B., McIvor, C.C., Peebles, E.B., Hollander, D.J., 2014. Site fidelity and condition metrics suggest sequential habitat use by juvenile common snook. *Mar. Ecol. Prog. Ser.* 509, 255–269.
- Camara, E.M., 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.
- Camara, E.M., Andrade-Tubino, M.F., Franco, T.P., Santos, L.N., Santos, A.F.G.N., Araújo, F.G., 2021. Scale sensitivity of environmental effects on the temporal beta diversity of fishes in tropical coastal lagoons. *Mar. Ecol. Prog. Ser.* 658, 195–217.
- Castro, B.M., Lorenzetti, J.A., Silveira, I.C.A. and Miranda, L.B. 2006. Estrutura termohalina e circulação na região entre Cabo de São Tomé (RJ) e o Chuí (RS). In 'O ambiente oceanográfico da plataforma continental e do talude na região sudeste-sul do Brasil'. (Eds C. L. D. B Rossi-Wongtschowski and L. S. P. Madureira) pp. 11-120. (EdUSP: São Paulo, BR).
- Chittaro, P.M., Finley, R.J., Levin, P.S., 2009. Spatial and temporal patterns in the contribution of fish from their nursery habitats. *Oecologia* 160, 49–61.
- 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.
- Correia, A.T., Pipa, T., Gonçalves, J.M.S., Erzini, K., Hamer, P.A., 2011. Insights into population structure of *Diplodus vulgaris* along the SW Portuguese coast from otolith elemental signatures. *Fish. Res.* 111 (1-2), 82–91.
- Correia, A.T., Ramos, A.A., Barros, F., Silva, G., Hamer, P., Morais, P., Cunha, R.L., Castilho, R., 2012. Population structure and connectivity of the European conger eel (*Conger conger*) across the north-eastern Atlantic and western Mediterranean: integrating molecular and otolith elemental approaches. *Mar. Biol.* 159, 1509–1525.
- Correia, A.T., Gomes, P., Gonçalves, J., Erzini, K., Hamer, P., 2012. Population structure of the black seabream *Spondyliosoma cantharus* along the south-west Portuguese coast inferred from otolith chemistry. *J. Fish. Biol.* 80 (2), 427–443.
- Correia, A.T., Moura, A., Triay-Portella, R., Santos, P.T., Pinto, E., Almeida, A.A., Muniz, A.A., 2021. Population structure of the chub mackerel (*Scomber colias*) in the NE Atlantic inferred from otolith elemental and isotopic signatures. *Fish. Res.* 234, 105785.
- Costa, M.R., Almeida, R.T., Mattos, T.M., Almeida, P.R.C., Monteiro, L.F.A., Andrade, D. H., Pinto, S.M., Tomás, A.R.G., & Monteiro-Neto, C. 2021. Diversidade de habitats e estrutura das assembleias de peixes e crustáceos. In: Costa M.R., Tubino R.A., Monteiro-Neto C. & Angelini R. (eds) *Pesca e sustentabilidade: passado, presente e futuro*. Rio de Janeiro. AH Edições. pp. 55-70.
- Cristo, V.N., da Silva Jr, G.C., Eger, G.Z., da Silveira, P.H.M., Menezes, J.M., 2015. Conceptual Model of Itaipuaçu Aquifer. *Maric. á - RJ Using Hydrogeochem. Hydrodyn. Tools. Rev. Bras. De Recur. H. Idricos* 20 (4), 1063–1075.
- Dahlgren, C.P., Kellison, G.T., Adams, A.J., Gillanders, B.M., Kendall, M.S., Layman, C. A., Serafy, J.E., 2006. Marine nurseries and effective juvenile habitats: concepts and applications. *Mar. Ecol. Prog. Ser.* 312, 291–295.
- 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.
- Daros, F.A., Spach, H.L., Sial, N.A., Correia, A.T., 2016. Otolith fingerprints of the coral reef fish *Stegastes fuscus* in southeast Brazil: a useful tool for population and connectivity studies. *Reg. Stud. Mar. Sci.* 3, 262–272.
- Daros, F.A., Condini, M.V., Altafin, J.P., de Oliveira Ferreira, F., Hostim-Silva, M., 2022. Fish otolith microchemistry as a biomarker of the world's largest mining disaster. *Sci. Total Environ.* 807, 151780.
- 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.
- Dias, P.P.B.B., Martins, M.V.A., Clemente, I.M.M.M., Carelli, T.G., Silva, F.S., Fontana, L. F., Lorini, M.L., Panigai, G., Pinheiro, R.H., Mendonça-Filho, J.G., Laut, L.L.M., 2017. Assessment of the Trophic State of Saquarema Lagoonal System, Rio de Janeiro (Brazil). *J. Sediment. Environ.* 2 (1), 49–64.
- Elsdon, T.S., Gillanders, B.M., 2003. Relationship between water and otolith elemental concentrations in juvenile black bream *Acanthopagrus butcheri*. *Mar. Ecol. Prog. Ser.* 260, 263–272.
- Elsdon, T.S., Gillanders, B.M., 2004. Fish otolith chemistry influenced by exposure to multiple environmental variables. *J. Exp. Mar. Biol. Ecol.* 313 (2), 269–284.
- Elsdon, T.S., Wells, B.K., Campana, S.E., Gillanders, B.M., Jones, C.M., Limburg, K.E., Walther, B.D., 2008. Otolith chemistry to describe movements and life-history parameters of fishes: hypotheses, assumptions, limitations and inferences. *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 *Chelidonichthys lucerna* (Linnaeus, 1758) a marine estuarine dependent fish? Insights from saccular otolith microchemistry. *Fishes* 8, 383.
- FIPERJ - Fundação Instituto de Pesca do Estado do Rio de Janeiro. 2022. Estatística Pesqueira do Estado do Rio de Janeiro. Consulta On-line. Projeto de Monitoramento da Atividade Pesqueira no Estado do Rio de Janeiro. Fundação Instituto de Pesca do Estado do Rio de Janeiro (FIPERJ). Disponível em: <http://pescarj.fundepag.br/>. Acesso em: "29-07-2022".
- Fontenelle, T., Corrêa, W.B., 2014. Impactos da urbanização no espelho d'água dos sistemas lagunares de Itaipu e de Piratininga, Niterói (RJ), entre 1976. *Bol. De. Geogr.* 32 (2), 150.
- 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.
- Freire, K.M.F., Tubino, R.A., Monteiro-Neto, C., Andrade-Tubino, M.F., Belrus, C.G., Tomás, A.R.G., Vieira, J.P., 2016. Brazilian recreational fisheries: current status, challenges and future direction. *Fish. Manag. Ecol.* 23 (3-4), 276–290.
- Friedrich, L.A., Halden, N.M., 2010. Determining exposure history of northern pike and walleye to tailings effluence using trace metal uptake in otoliths. *Environ. Sci. Technol.* 44 (5), 1551–1558.
- Gerlach, M.J., Engelhart, S.E., Kemp, A.C., Moyer, R.P., Smoak, J.M., Bernhardt, C.E., Cahill, N., 2017. Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. *Mar. Geol.* 390, 254–269.
- Gibb, F.M., Régner, T., Donald, K., Wright, P.J., 2016. Connectivity in the early life history of sandeel inferred from otolith microchemistry. *Journal of Sea Research.*
- Gomes, L.E.O., Correa, L.B., Sá, F., Neto, R.R., Bernardino, A.F., 2017. The impacts of the Samarco mine tailing spill on the Rio Doce estuary, Eastern Brazil. *Mar. Pollut. Bull.* 120, 28–36.

- Halden, N.M., Mejia, S.R., Babaluk, J.A., Reist, J.D., Kristofferson, A.H., Campbell, J.L., Teesdale, W.J., 2000. Oscillatory zinc distribution in Arctic char (*Salvelinus alpinus*) otoliths: The result of biology or environment? *Fish. Res.* 46 (1-3), 289–298.
- Hicks, A.S., Closs, G.P., Swearer, S.E., 2010. Otolith microchemistry of two amphidromous galaxiids across an experimental salinity gradient: a multi-element approach for tracking diadromous migrations. *J. Exp. Mar. Biol. Ecol.* 394 (1-2), 86–97.
- 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. *Rev. Fish. Sci. Aquac.* 29 (4), 445–477.
- Izzo, C., Reis-Santos, P., Gillanders, B.M., 2018. Otolith chemistry does not just reflect environmental conditions: A meta-analytic evaluation. *Fish Fish* 19 (3), 441–454.
- Knoppers, B.A., W.F.L. Souza, W. Ekau, A.G. Figueiredo & A. Soares-Gomes. 2009. A Interface Terra-Mar do Brasil. In: Pereira, R.C.C. & A. Soares-Gomes (orgs.). *Biologia marinha*. Interciência, Rio de Janeiro, pp.529-553.
- Kritzer, J.P., Sale, P.F., 2006. The future of metapopulation science in marine ecology. *Mar. Metapopulations* 517–529.
- Lacerda, L.D., Abrão, J.J., Bernat, M., & Fernex, F., 1999. Biogeodynamics of heavy metals in the Lagoons of Eastern Rio de Janeiro state, Brazil. In: Knoppers, B., Bidone, E.D., Abrão, J.J. (Eds.), *Environmental Geochemistry of Coastal Lagoons Systems*. Rio de Janeiro, Brazil, pp. 123–154.
- Lahaye, Y., Lambert, D., Walters, S., 1997. Ultraviolet laser sampling and high resolution inductively coupled plasma-mass spectrometry of NIST and BCR-2G glass reference materials. *Geostand. Newsl.* 21 (2), 205–214.
- Laugier, F., Feunteun, E., Pecheyran, 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.
- Leisch, F., Hornik, K., & Ripley, B.D., 2009. Mixture and flexible discriminant analysis. R package version 0.4-2. <https://cran.r-project.org/web/packages/mda/mda.pdf>.
- Lenz, C., Jilbert, T., Conley, D.J., Slomp, C.P., 2015. Hypoxia-driven variations in iron and manganese shuttling in the Baltic Sea over the past 8 kyr. *Geochem., Geophys., Geosystems* 16 (10), 3754–3766.
- Ley, J.A., Rolls, H.J., 2018. Using otolith microchemistry to assess nursery habitat contribution and function at a fine spatial scale. *Mar. Ecol. Prog. Ser.* 606, 151–173.
- Ley, J.A., McIvor, C.C., Peebles, E.B., & Rolls, H. 2010. Defining fish nursery habitats: an application of otolith elemental fingerprinting in Tampa Bay, Florida. In *Bay Area Scientific Information Symposium*, Tampa Bay, Florida (pp. 331-346).
- Lima, J.S., Zappes, C.A., Di Benedetto, A.P.M., Zalmon, I.R., 2018. Artisanal fisheries and artificial reefs on the southeast coast of Brazil: Contributions to research and management. *Ocean Coast. Manag.* 163, 372–382.
- Limburg, K.E., Walther, B.D., Lu, Z., Jackman, G., Mohan, J., Walther, Y., Schmitt, A.K., 2015. In search of the dead zone: use of otoliths for tracking fish exposure to hypoxia. *J. Mar. Syst.* 141, 167–178.
- Lowerre-Barbieri, S., Villegas-Rios, D., Walters, S., Bickford, J., Cooper, W., Muller, R., Trotter, A., 2014. Spawning site selection and contingent behavior in common snook, *Centropomus undecimalis*. *PLoS One* 9 (7), e101809.
- Maciel, T.R., Vianna, M., Carvalho, B.M., Miller, N., Avigliano, E., 2021. Integrated use of otolith shape and microchemistry to assess *Genidens barbuis* fish stock structure. *Estuar., Coast. Shelf Sci.* 261, 107560.
- Madureira, L., Azevedo, J.L., Brum, A., Coletto, J., Pinho, M., Varela, C., 2020. The oceanographic dynamics of the skipjack tuna fishing area in the Southwest Atlantic. In: Madureira, L., Monteiro-Neto, C. (Eds.), *Sustainability of Skipjack Tuna Fishery in Brazil*. Paco, Jundiá SP, pp. 15–46.
- 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 Lagoas do Estado do Rio de Janeiro (RJ). In: Schobbenhaus, C., Silva, C.R. (Eds.), *Projeto Geoparques do Brasil: Propostas*. CPRM, Rio de Janeiro, pp. 686–745.
- Medeiros, R., Oliveira, C.D., Souto, D., Rangely, J., Fabrè, N.N., 2021. Growth stanza in fish life history using otoliths shape: the protandric *Centropomus* case (Carangaria: Centropomidae). *Neotrop. Ichthyol.* 19 (4), e200145 <https://doi.org/10.1590/1982-0224-2020-0145>.
- Menezes, A.A.S., Lin, C.F., Silva, C., dos Santos, R.A., 2012. Aspectos socioeconômicos relacionados à pesca amadora de robalo (*Centropomus undecimalis* e *C. parallelus*) na Baía da Babitonga, Santa Catarina, Brasil. *Rev. CEPSUL-Biodivers. e Conserv. ção Mar.* 3 (1), 22–44.
- Milton, D.A., 2009. Living in two worlds: diadromous fishes and factors affecting population connectivity between tropical rivers and coasts. In: Nagelkerken, I. (Ed.), *Ecological Connectivity among Tropical Coastal Ecosystems*. Springer, London, pp. 325–355.
- Moreira, C., Froufe, E., Vaz-Pires, P., Triay-Portella, R., Méndez, A., Castro, J.P., Correia, A.T., 2022. Unravelling the spatial-temporal population structure of *Trachurus picturatus* across the North-East Atlantic using otolith fingerprinting. *Estuar., Coast. Shelf Sci.* 272, 107860.
- Moura, A., Muniz, A.A., Mullins, R., Wilson, J.M., Vieira, R.P., Almeida, A.A., Pinto, E., Brummer, G.J.A., Gaever, P.V., Gonçalves, J.M.S., Correia, A.T., 2020. Population structure and dynamics of the Atlantic mackerel (*Scomber scombrus*) in the North Atlantic inferred from otolith chemical and shape signatures. *Fish. Res.* 230, 105621.
- Muller, R.G., Taylor, R.G., 2000. The 2000 stock assessment update of common snook, *Centropomus undecimalis*. Florida Marine Research Institute, p. 49.
- Nagelkerken, I., Blaber, S.J.M., Bouillon, S., Green, P., Haywood, M., Kiston, L.G., Meynecke, J.-O., Pawlik, J., Penrose, H.M., Sasekumar, A., Somerfield, P.J., 2005. The habitat function of mangroves for terrestrial and marine fauna: a review. *Aquat. Bot.* 89, 155–185. <https://doi.org/10.1016/j.aquabot.2007.12.007>.
- 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, Version 2* (9), 1–295.
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J., 2011. Iolite: Freeware for the visualization and processing of mass spectrometric data. *J. Anal. At. Spectrom.* 26, 2508–2518.
- Patterson, H.M., Taylor, R.G., McBride, R.S., 2005. Coastal origin of common snook, *Centropomus undecimalis*, in Florida Bay. *Gulf and Caribbean. Research* 17 (1), 25–30.
- Pearce, N.J., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R., Chenery, S.P., 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. *Geostand. Newsl.* 21 (1), 115–144.
- Pereira, M.E.G.S., Silva, B.B., Rocha, R.M., Asp-Neto, N.E., Silva, C.S., Nunes, Z.M.P., 2015. Bioecologia do robalo-flexa, *Centropomus undecimalis*, em lagoa costeira tropical no norte do Brasil. *Bol. do Inst. De. Pesca, São Paulo* 41 (3), 457–469.
- Pereira, M.E.G.S., Santos, F.J.S., Holanda, F.C., Miranda, J., Lutz, I.A.F., Barboza, R.S.L., Evangelista-Gomes, G., 2020. A pesca do Camurim *Centropomus undecimalis* (Centropomidae–Perciformes) no litoral amazônico brasileiro: contribuição dos atores da pesca para o manejo pesqueiro. *Res., Soc. Dev.* 9 (10) e6189108945-6189108945.
- Perera-García, M.A., Mendoza-Carranza, M., Contreras-Sánchez, W.M., Huerta-Ortiz, M., Pérez-Sánchez, E., 2011. Reproductive biology of common snook *Centropomus undecimalis* (Perciformes: Centropomidae) in two tropical habitats. *Rev. De. Biol. ía Trop.* 59 (2), 669–681.
- Peters, K.M., Matheson Jr, R.E., Taylor, R.G., 1998. Reproduction and early life history of common snook, *Centropomus undecimalis* (Bloch), in Florida. *Bull. Mar. Sci.* 62 (2), 509–529.
- R Development Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for statistical computing, Vienna, Austria (Accessed 01 May 2021). <http://www.R-project.org>.
- Ranaldi, M.M., Gagnon, M.M., 2008. Zinc incorporation in the otoliths of juvenile pink snapper (*Pagrus auratus* Forster): the influence of dietary versus waterborne sources. *J. Exp. Mar. Biol. Ecol.* 360, 56–62. <https://doi.org/10.1016/j.jembe.2008.03.013>.
- Ray, G.C., 2005. Connectivities of estuarine fishes to the coastal realm. *Estuar., Coast. Shelf Sci.* 64 (1), 18–32.
- Reis-Santos, P., Tanner, S.E., Vasconcelos, R.P., Elsdon, T.S., Cabral, H.N., Gillanders, B.M., 2013. Connectivity between estuarine and coastal fish populations: contributions of estuaries are not consistent over time. *Mar. Ecol. Prog. Ser.* 491, 177–186.
- 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.
- Sale, P.F., Cowen, R.K., Danilowicz, B.S., Jones, G.P., Kritzer, J.P., Lindeman, K.C., Planes, S., Polunin, N.V.C., Russ, G.R., Sadovy, Y.J., Steneck, R.S., 2005. Critical science gaps impede use of no-take fishery reserves. *Trends Ecol. Evol.* 20 (2), 74–80.
- 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.
- Schroeder, R., Schwingel, P.R., Pinto, E., Almeida, A., Correia, A.T., 2022. Stock structure of the Brazilian sardine *Sardinella brasiliensis* from Southwest Atlantic Ocean inferred from otolith elemental signatures. *Fish. Res.* 248, 106192.
- Schroeder, R., Avigliano, E., Volpedo, A.V., Fortunato, R.C., Barrulas, P., Daros, F.A., Schwingel, P.R., Dias, M.C., Correia, A.T., 2023. Lebranche mullet *Mugil liza* population structure and connectivity patterns in the southwest Atlantic Ocean using a multidisciplinary approach. *Estuar., Coast. Shelf Sci.* 288, 108368.
- Secor, D.H., Dean, J.M., Laban, E.H., 1992. Otolith removal and preparation for microstructure examination. In: Stevenson, D.K., Campana, S.E. (Eds.), ‘Otolith Microstructure Examination and Analysis’. Canadian Special Publication of Fisheries and Aquatic Sciences, Ottawa, pp. 19–57.
- Shaw, T.J., Moore, W.S., Kloepper, J., Sochaski, M.A., 1998. The flux of barium to the coastal waters of the southeastern USA: the importance of submarine groundwater discharge. *Geochim. Et. Cosmochim. Acta* 62, 3047–3054.
- Silva, L.B.C., Molisani, M.M., 2019. Revisão histórica sobre o estado trófico de lagoas costeiras do estado do Rio de Janeiro. *Campos dos Goytacazes. RJ: Ess.* 105.
- Silva, L.M.C., Machado, I.C., Tutui, S.L.S., e Tomás, A.R.G., 2019. Ethnobiological calendar of snook fish, according to the fishermen of the estuarine areas of Baixada Santista (SP). *Atas CIAIQ2019, Invest. ção Qual. em Ciências Sociais//Invest. óN. Cual. En. Cienc. Soc. //Vol.* 3.
- Silva, R.A.G., Rosman, P.C.C., 2016. Viabilidade hidro-sedimentológica de um canal de maré projetado no oeste da Lagoa de Araruama-RJ. *RBRH* 21, 25–35.
- 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. *J. Sea Res.* 158, 101873.
- Souza, M.F., Kjerfve, B., Knoppers, B., de Souza, W.F.L., Damasceno, R.N., 2003. Nutrient budgets and trophic state in a hypersaline coastal lagoon: Lagoa de Araruama, Brazil. *Estuar., Coast. Shelf Sci.* 57 (5-6), 843–858.
- Stevens, P.W., Blewett, D.A., Poulakis, G.R., 2007. Variable habitat use by juvenile common snook, *Centropomus undecimalis* (Pisces: Centropomidae): applying a life-history model in a southwest Florida estuary. *Bull. Mar. Sci.* 80 (1), 93–108.
- Sturrock, A.M., Hunter, E., Milton, J.A., EIMF, Johnson, R.C., Waring, C.P., Trueman, C.N., 2015. Quantifying physiological influences on otolith microchemistry. *Methods Ecol. Evol.* 6 (7), 806–816.
- Taylor, R.G., Whittington, J.A., Grier, H.J., Crabtree, R.E., 2000. Age, growth, maturation, and protandric sex reversal in common snook, *Centropomus undecimalis*, from the east and west coasts of South Florida. *Fish. Bull.* 98 (3), 612–612.
- Thomas, O.R., Ganio, K., Roberts, B.R., Swearer, S.E., 2017. Trace element–protein interactions in endolymph from the inner ear of fish: implications for environmental reconstructions using fish otolith chemistry. *Metallomics* 9 (3), 239–249.

- Thomas, O.R., Thomas, K.V., Jenkins, G.P., Swearer, S.E., 2020. Spatio-temporal resolution of spawning and larval nursery habitats using otolith microchemistry is element dependent. *Mar. Ecol. Prog. Ser.* 636, 169–187.
- 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.
- Tucker, J.W. Jr. and S.M. Warlen. 1986. Aging of Common Snook *Centropomus undecimalis* Larvae Using Sagittal Daily Growth Rings. *Northeast Gulf Science* 8 (2). Retrieved from <https://aquila.usm.edu/goms/vol8/iss2/12>.
- Valle-Levinson, A., Dutton, A., Martin, J.B., 2017. Spatial and temporal variability of sea level rise hot spots over the eastern United States. *Geophys. Res. Lett.* 44 (15), 7876–7882.
- Vasconcelos, R.P., Reis-Santos, P., Costa, M.J., Cabral, H.N., 2011. Connectivity between estuaries and marine environment: Integrating metrics to assess estuarine nursery function. *Ecol. Indic.* 11 (5), 1123–1133.
- Vaz-dos-Santos, A.M., 2015. Otolitos en estudios de edad y crecimiento en peces. In: Volpedo, A.V., Vaz-dos-Santos, A.M. (Eds.), *Métodos de estudios con otolitos: principios y aplicaciones*. Buenos Aires, pp. 303–332.
- Vignon, M., 2012. Ontogenetic trajectories of otolith shape during shift in habitat use: Interaction between otolith growth and environment. *J. Exp. Mar. Biol. Ecol.* 420, 26–32.
- Walsh, C.T., Gillanders, B.M., 2018. Extrinsic factors affecting otolith chemistry—implications for interpreting migration patterns in a diadromous fish. *Environ. Biol. Fishes* 101, 905–916.
- Walther, B.D., 2019. The art of otolith chemistry: interpreting patterns by integrating perspectives. *Mar. Freshw. Res.* 70 (12), 1643–1658.
- Webb, S.D., Woodcock, S.H., Gillanders, B.M., 2012. Sources of otolith barium and strontium in estuarine fish and the influence of salinity and temperature. *Mar. Ecol. Prog. Ser.* 453, 189–199.
- Woodcock, S.H., Munro, A.R., Crook, D.A., Gillanders, B.M., 2012. Incorporation of magnesium into fish otoliths: determining contribution from water and diet. *Geochim. Et. Cosmochim. Acta* 94, 12–21.
- Woodson, L.E., Wells, B.K., Grimes, C.B., Franks, R.P., Santora, J.A., Carr, M.H., 2013. Water and otolith chemistry identify exposure of juvenile rockfish to upwelled waters in an open coastal system. *Mar. Ecol. Prog. Ser.* 473, 261–273.
- Yoshinaga, J., Nakama, A., Morita, M., Edmonds, J.S., 2000. Fish otolith reference material for quality assurance of chemical analyses. *Mar. Chem.* 69, 91–97.
- Young, J.M., Yeiser, B.G., Whittington, J.A., 2014. Spatiotemporal dynamics of spawning aggregations of common snook on the east coast of Florida. *Mar. Ecol. Prog. Ser.* 505, 227–240.