Leave forever or return home? The case of the whitemouth croaker *Micropogonias furnieri* in coastal systems of southeastern Brazil indicated by otolith microchemistry

Taynara P. Franco[a], Cristiano Q. Albuquerque[b], Rosa S. Santos[a], Tatiana D. Saint'Pierre[c], Francisco G. Araújo[a],*

[a] *Universidade Federal Rural do Rio de Janeiro, Departamento de Biologia Animal, Laboratório de Ecologia de Peixes, 23897-030, Seropédica, RJ, Brazil*
[b] *Universidade Federal Rural do Semi-Árido, Departamento de Ciências Animais, Escola Superior de Agricultura de Mossoró, 59.625-900, Mossoró, RN, Brazil*
[c] *Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Química, Laboratório de Espectrometria Atômica, 22451-900, Rio de Janeiro, RJ, Brazil*

ABSTRACT

Movements of coastal fish species between estuarine systems (rearing grounds) and adjacent platforms (spawning grounds) are complex and can be influenced by multiple biotic and abiotic factors associated with the life cycle of each species. Understanding fish movement patterns between these habitats is crucial for sustainable management of these resources. We aimed to identify movement patterns of the whitemouth croaker *Micropogonias furnieri,* an important fishery resource along the southeastern Brazilian coast, through characterization of elemental concentration profiles in otoliths. Signal intensity ratios of $Sr^{86}:Ca^{43}$ and $Ba^{138}:Ca^{43}$, measured by a Laser ablation inductively coupled to a plasma mass spectrometry (LA-ICPMS), were analysed. Juveniles and adults fish from three semi-enclosed systems (two bays and one coastal lagoon) and adults from nine adjacent coastal areas were examined. Three main behavioural patterns were identified: 1) Marine Migrant, with a unique and definitive movement from the estuarine area towards the adjacent platform when adult; 2) Estuarine Visitor, with movements from the estuarine area towards the adjacent platform when adult but also performing excursions back to the estuarine areas and back again to the adjacent platform; and 3) Nearshore Resident, with occurrence in the adjacent coastal areas that are influenced by estuarine systems. Estuarine areas with large sea connections (e.g., bays) favour more frequent fish entrances and exits compared with coastal lagoons that have a narrow sea connection. The high eurioic condition and capacity related to adapting to different environmental conditions were detected in this study for *M. furnieri*, a likely strategy to maintain variation in life histories and successfully adapt to coastal marine systems.

1. Introduction

Otoliths are calcified structures that function in balancing and hearing in all teleost fishes, incorporating minor trace elements into their calcium carbonate matrix (Campana, 1999; Secor and Rooker, 2000; Sturrock et al., 2012). Some elements (e.g., Sr and Ba) are incorporated at rates related to their environmental concentrations, thus reflecting local availability in the water (Walther and Thorrold, 2006; Brown and Severin, 2009; Miller, 2011; Tulp et al., 2013). Because of these characteristics, otolith elemental composition shows consistent spatial signatures of the environments used by a given fish species during its lifetime (Bradbury et al., 2011; Walther and Limburg, 2012). Recently, the use of otolith microstructure and chemistry as complementary natural tags has become increasingly valuable for understanding the migration patterns of fish across freshwater, estuarine areas, and marine environments (Tanner et al., 2013; Avigliano et al., 2015; Daros et al., 2016; Callicó Fortunato et al., 2017). Variations in Sr:Ca and Ba:Ca ratios along the otolith growth axis have been interpreted as fish movements across salinity gradients in several fish species (Morales-Nin et al., 2012; Avigliano et al., 2017). For the majority of coastal systems, strontium (Sr) and barium (Ba) water concentrations are inversely related, with higher Sr and lower Ba concentrations in marine compared to fresh waters (Brown and Severin, 2009; Miller, 2011; Walsh and Gillanders, 2018). These elements standardised to calcium (Ca) have been commonly used to reconstruct diadromous migrations (Elsdon and Gillanders, 2005; McCulloch et al., 2005;

* Corresponding author.
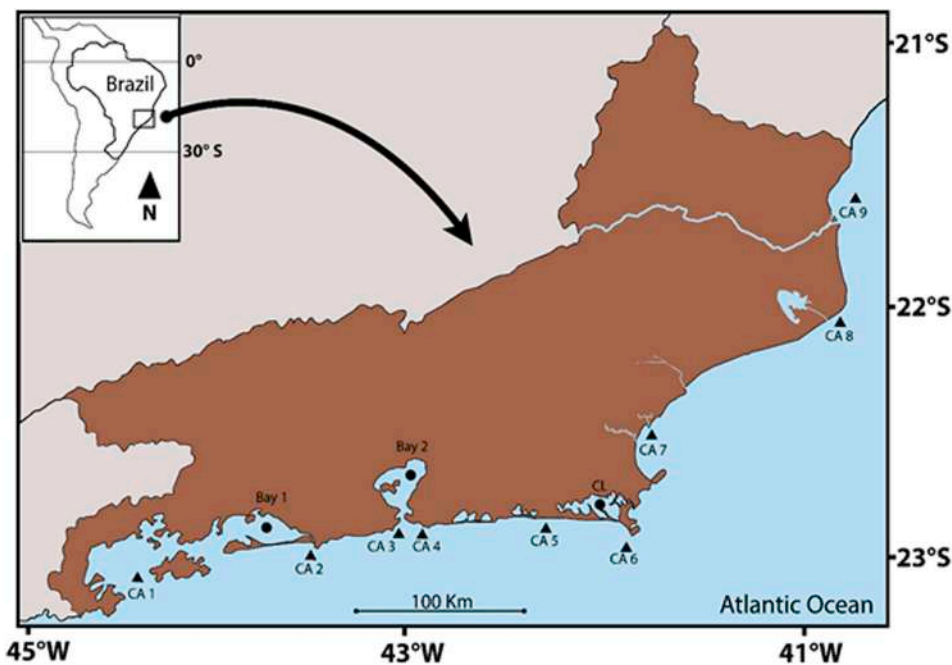*E-mail addresses:* gersonufrrj@gmail.com, gerson@ufrrj.br (F.G. Araújo).

Fig. 1. Location of three sampled estuarine systems (Sepetiba Bay, Bay 1; Guanabara Bay, Bay 2; and Araruama coastal lagoon, CL) and nine coastal areas (CA1, Ilha Grande; CA2, Barra de Guaratiba; CA3, Copacabana; CA4, Itaipu; CA5, Saquarema; CA6, Arraial do Cabo; CA7, Rio das Ostras; CA8, Farol de São Tomé; and CA9, Campos dos Goytacazes) in Rio de Janeiro State.

Walther and Limburg, 2012). Therefore, otolith elemental signatures serve as a sensitive natural tag and can be used to track the entire life history of a fish.

Many species of fish perform movements between habitats of different salinities during the life cycle. In many cases, these movements can be more complex than has been previously understood. Recent studies have shown certain flexibility of habitat use and timing of migration of some fish species (Avigliano et al., 2018; Mai et al., 2018), and such behaviour may confer resilience to many migratory fish species (Secor, 1999; Secor and Piccoli, 2007; Schindler et al., 2010). In the case of the loss of habitats because of anthropogenic influences and/or natural causes, the species would have contingents capable of surviving by the differentiation in the use of habitats. The knowledge of alternative migratory routes of commercially and ecologically important species may substantially help the effectiveness of management strategies.

Micropogonias furnieri (Desmarest, 1823) is an euryhaline fish species that uses different coastal environments during its life cycle (Vazzoler, 1991; Costa et al., 2013). The wide range of its geographical distribution, from Costa Rica to Argentina (Volpedo and Cirelli, 2006; Froese and Pauly, 2017), and an effective osmoregulatory system (Diaz et al., 2008) allow this species to use a variety of habitats, such as estuaries, bays, coastal lagoons and the inner continental shelf. Spawning occurs in the inner platform near estuarine semi-enclosed systems, and the early juveniles recruit in shallow estuarine environments, thus benefiting from favourable conditions for feeding and shelter (Costa and Araújo, 2003). Young fish use estuarine areas that are comparatively safe and productive habitats and that provide adaptive advantages as nursery grounds. When they reach larger sizes, the fish move to spawn in the inner platform (Vazzoler, 1991; Costa and Araújo, 2003; Albuquerque et al., 2012).

Although the inner shelf close to estuarine areas serves as the main reproduction grounds, spawning has also been registered in estuarine regions in some temperate estuaries of the Uruguayan coast and in the Rio de la Plata estuary (Macchi et al., 1996; Vizziano et al., 2002; Jaureguizar et al., 2008). There are indications that some adult individuals could remain within estuaries, tending to mature early (Castello, 1986; D'Anatro et al., 2011). Based on fishermen local knowledge, this species shows a migratory pattern to spawn in pelagic coastal waters and has a wide reproductive period (Silvano et al.,

2006). However, most studies on the use of nursery areas and movements towards the adjacent platform are based on the patterns of population size structure (but see Albuquerque et al., 2010, 2012). The period that the species spends within the semi-enclosed systems is still not clear, although some studies point to estuarine use during the early life and spawning in the inner shelf along the Brazilian southern-southeastern coast (Cavole and Haimovici, 2015).

The analysis of otolith microchemistry has been used to demonstrate habitat use, migration and connectivity of many fish populations among freshwater and estuarine and marine systems (Chang et al., 2004; Tulp et al., 2013; Davoren and Halden, 2014; Callicó Fortunato et al., 2017). Some of these studies demonstrate the existence of population contingents with specific migratory behaviours and highlight that migratory plasticity is more usual than previously thought. The dusky grouper *Epinephelus marginatus* (Lowe, 1834) was reported as having three contrasting migratory patterns (Condini et al., 2016). Otolith microchemistry has also revealed that the fat snook *Centropomus paralelus* Poey, 1860 can occupy diverse salinity habitats and migrates among marine, brackish and freshwater areas (Daros et al., 2016).

The use of otolith microchemistry to assess patterns of movements of *M. furnieri* was studied in the southwestern Atlantic Ocean (Albuquerque et al., 2012). This study suggested that *M. furnieri* is dependent upon estuaries and that fish migrate to coastal waters from ages 2 to 4. However, the suggested timing for the migration is arguable given the uncertainties regarding the formation of the first annual increment in their otoliths (Cavole and Haimovici, 2015). The species occurs along a large latitudinal range and is therefore subject to diverse oceanographic and freshwater runoff characteristics that may affect its migratory behaviour. The present study aimed to test the hypothesis that there is individual differentiation in the use of the estuarine systems by *M. furnieri*, with some contingents returning to the estuarine environment after the adult stage, whereas others stay permanently in the adjacent inner platform after migrating from the estuarine environments.

2. Materials and methods

2.1. Study area

Three semi-enclosed estuarine areas in the Rio de Janeiro State were

Table 1

Salinity ranges and statistics for the Sr:Ca ratios from the otolith edges for different coastal systems. TL, Total length; Min-Max, Minimum-Maximum, SD, standard deviation.

System	n	Size range (TL, cm)	Salinity Min-Max	Sr:Ca Mean $\pm$ SD	Sr:Ca Min-Max
Mirim Lagoon[a]	4	42.5–44.5	0–0.5	0.15 $\pm$ 0.01	0.04–0.19
Patos Lagoon[a]	6	13.3–24.4	5–20	0.32 $\pm$ 0.02	0.23–0.40
Bay 2	39	18.5–26.8	21–35	0.49 $\pm$ 0.08	0.35–0.60
Bay 1	36	12.5–32.0	28–35	0.53 $\pm$ 0.18	0.28–0.73
Coastal Lagoon	22	7.3–23.0	32–62	0.55 $\pm$ 0.13	0.38–0.72
Coastal Areas 3, 7, 8	28	18.0–47.5	34–35	0.46 $\pm$ 0.08	0.35–0.62
Coastal Area 6 - adjacent platform	13	27.2–66.0	36	0.65 $\pm$ 0.19	0.60–0.98

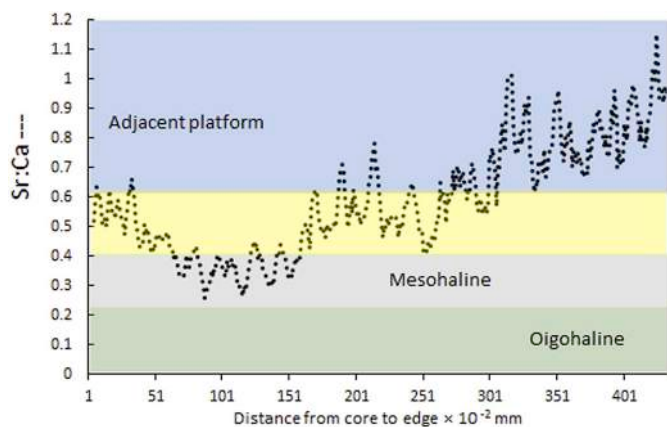[a] Otoliths information following Albuquerque et al. (2010).

Fig. 2. Range of the Sr:Ca ratios for the saline gradient for *Micropogonias furnieri*.

Table 2

Statistics on the size and age of *M. furnieri* otoliths in the estuarine and coastal systems in the Rio de Janeiro State. n, number of individuals. Min-Max, minimum-maximum. SD, standard deviation; TL, total length.

Systems	n	TL (cm)		Annual growth increments	
		Min-Max	Mean $\pm$ SD	Min-Max	Mean $\pm$ SD
Estuarine systems					
Bay 1	36	12.5–32.0	23.6 $\pm$ 5.8	0–8	2.8 $\pm$ 2.4
Bay 2	39	18.5–26.8	21.3 $\pm$ 1.7	0–9	3.8 $\pm$ 2.4
Coastal Lagoon	22	7.3–23.0	14.1 $\pm$ 4.6	0–1	0.2 $\pm$ 0.3
Coastal systems					
Coastal Area 1	19	28.5–58.5	41.6 $\pm$ 9.7	4–17	8.4 $\pm$ 2.9
Coastal Area 2	10	29.0–54.0	36.4 $\pm$ 7.9	3–8	4.2 $\pm$ 1.9
Coastal Area 3	9	37.2–47.5	44.5 $\pm$ 2.9	3–9	6.8 $\pm$ 1.9
Coastal Area 4	31	33.0–40.0	37.1 $\pm$ 2.1	2–11	4.4 $\pm$ 2.2
Coastal Area 5	28	28.0–47.0	34.2 $\pm$ 4.8	2–9	4.5 $\pm$ 2.5
Coastal Area 6	13	27.2–66.0	45.4 $\pm$ 8.9	2–22	7.0 $\pm$ 4.5
Coastal Area 7	7	27.2–38.5	31.3 $\pm$ 4.1	4–8	4.8 $\pm$ 1.8
Coastal Area 8	12	18.0–23.6	20.5 $\pm$ 1.5	1–4	1.61 $\pm$ 0.9
Coastal Area 9	7	43.1–61	52.3 $\pm$ 6.6	4–13	8.5 $\pm$ 2.9

selected (Fig. 1): (1) Sepetiba Bay (latitude 23°03'–23°01′ S; longitude 43°01'–43°36′ W) with an area of 450 km² and a major freshwater contributor to the Guandu River (flow approximately 130 m³/sec) and with a salinity ranging from 28 in the inner zone to 33 in the outer zone (Araújo et al., 2016); (2) Guanabara Bay (22°41'–22°03′S; 43°16'–43º01'W) with 384 km² of area and a salinity ranging from 19 to 35 (Kjerfve et al., 1997); and (3) Araruama Lagoon (22°54'–22°52′S; 42°23'–42°00'W), a hypersaline lagoon with an area of 210 km² and

with little influence from continental waters (Kjerfve and Kjerfve, 1994) and a salinity ranging from 32 to 61. All semi-enclosed areas are permanently connected to the sea by a wide area (bay) or a narrow channel (coastal lagoon).

In addition to these three semi-enclosed systems, nine adjacent coastal areas were selected, all of them with salinity ranging from 34 to 36: two next to the Sepetiba Bay (coastal area 1-CA1, Ilha Grande; and CA2, Barra de Guaratiba); two next to the Guanabara Bay (CA3, Copacabana Beach; and CA4, Itaipu Beach); one next to a little coastal lagoon (CA5, Saquarema, 21 km², salinity 22–40); one next to a hypersaline coastal lagoon (210 km², salinity 35–65) and an upwelling area (CA6, Arraial do Cabo, offshore, i.e., approximately 50 km from the coastline); one next to a small estuary (CA7, Rio da Ostras); one next to the outlet of a coastal lagoon (CA8, Farol de São Tome); and one next to a river estuary with a flow of approximately 700 m³/sec (CA9, Campos dos Goytacazes) (Fig. 1).

2.2. Sample collection

A total of 233 individuals captured from artisanal catches along the coast of Rio de Janeiro State, from 2010 to 2015, were analysed. Of these, 97 individuals were captured in the three semi-enclosed systems (estuarine areas), whereas 136 adult individuals were captured in the adjacent platform (nearshore). In the semi-enclosed systems, 4 juveniles, 22 subadults and 10 adults were examined from the Bay 1, 39 subadults from Bay 2, and 16 juveniles and 8 subadults from the coastal lagoon (CL 1). All individuals from the coastal areas were adults with exception of CA8 where only subadults were collected.

Individuals were assigned into four life stage groups, following Vazzoler (1991): (1) recruits < 7 cm total length (TL); (2) juveniles between 7 and 15 cm TL; (3) subadults between 15 and 27.0 cm TL, and (4) adults > 27.0 cm TL. Counts of otolith annual increments (annuli) were performed to confirm the fish life stage (Schwingel and Castello, 1990; Santos et al., 2017). The purpose of capturing fish in different life stages inside the estuarine systems was to assess the eventual movements of the juveniles inside these semi-enclosed systems and possible departures and returns of the subadults and adults.

2.3. Otolith preparation and chemistry analyses

After capture, fish were preserved on ice and transported to the laboratory. The total length (TL, in centimetres) and the total weight (in grams) were measured, and the sagittae otoliths were removed. The left sagitta otolith was washed in distilled water, dried, included in acrylic resin and sliced to the core in 0.5 mm thin sections using a low speed saw (IsoMet-Buehler). The slices were glued on glass slides with fast drying glue and sanded with 6000, 8000 and 12000 grit sand papers. Otolith slices were cleaned with ultrapure DI water (Milli-Q, Millipore, Bedford, USA). The slides were then dried in a laminar flow cabinet before analyses.

Elemental analyses were conducted in a 266 nm LSX-100 (CETAC) laser ablation system coupled to a NexIon 300X (PerkinElmer, USA) inductively coupled plasma mass spectrometer. The operational parameters were RF power at 1100 W and argon flow rates of 1.2 mL min^{-1} nebulizer gas, 17 L min^{-1} plasma gas and 1 L min^{-1} auxiliary gas. The LA speed was 25 μm × s^{-1}. The measured isotopes were ^{86}Sr and ^{138}Ba and ^{43}Ca as internal standard. We opted to use ^{43}Ca, ^{86}Sr because other isotope intensities (e.g., ^{40}Ca, ^{44}Ca and ^{88}Sr) were very high under the used laser setup, sometimes saturating the ICPMS detector. The precision of the analysis was evaluated by estimating the relative standard deviation (RSD) of ten standard consecutive measurements of the standard reference material (SRM) NIST 1834 (Fused simulated ore). A RSD of 4.1% was obtained for Ca, 3.6% for Sr and 12.4% for Ba, which were considered acceptable. Blank ablations were measured during 50 s after every 10 otolith ablations to check for the background intensities. The profiles between core-edge from each otolith were performed in a
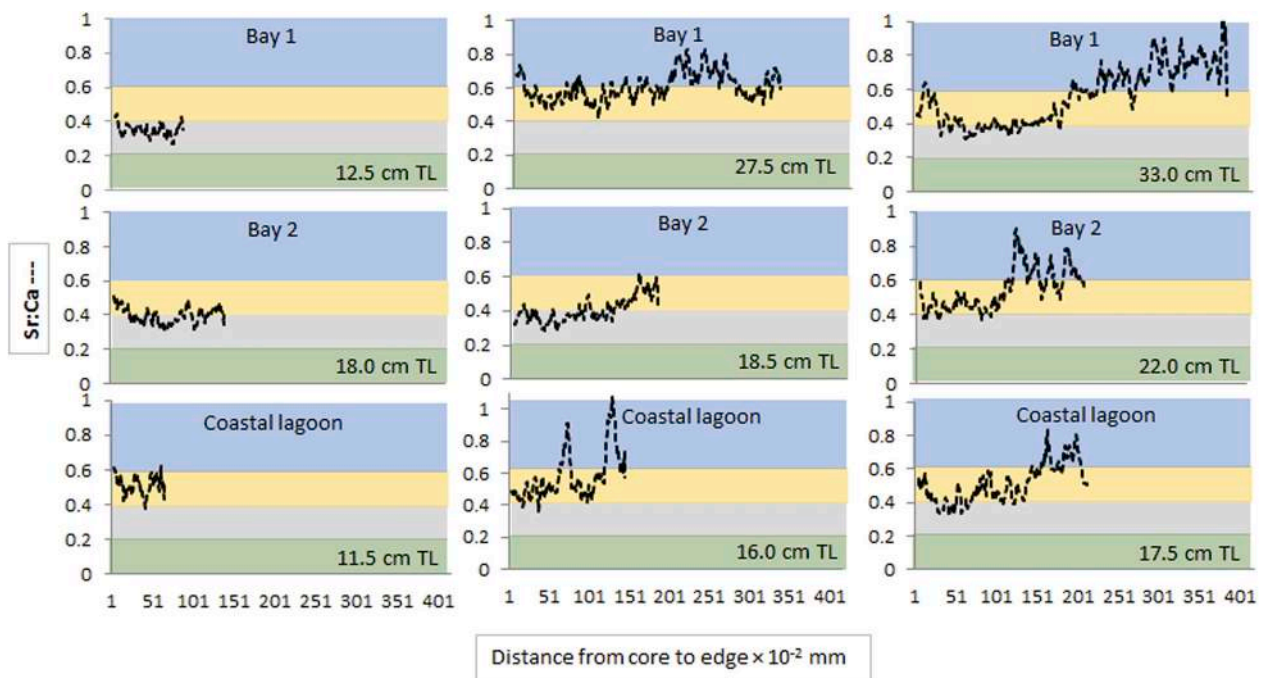
Fig. 3. Sr:Ca ratio profiles of fishes from three estuarine areas. The youngest individuals are in the first column and the oldest in the third column. Individual size (Total length, TL) and system also included in each graph.

transect diameter of 20 μm.

2.4. Data analysis

To validate the Sr:Ca ratios as an indicator of whitemouth croaker habitat use and movement patterns, we used the last 5 values and the minimum and maximum values of the otolith elemental relations of intensity for each environment (freshwater, mesohaline, polyhaline and adjacent platform). The last 5 values refer to the edge of the otolith in individuals of different life stages and represent the material more recently deposited into the otolith. Freshwater signatures were based on otoliths from Mirim Lagoon (a freshwater coastal lagoon). For the estuarine areas, chemical signatures were based on fish from the meso/polyhaline areas of Rio de Janeiro (Bay 1 and Bay 2) and Patos Lagoon, southern Brazil. Marine signatures with a strong influence of estuarine signatures were based on otoliths from coastal areas (CA3, CA7 and CA8). For the adjacent platform, individuals captured in Coastal Area 6, the farthest site from the coastline (approximately 50 km), were used (Table 1). The ratios of Sr:Ca up to 0.2 were considered oligohaline, between 0.2 and 0.4 mesohaline, 0.4 and 0.6 polyhaline and > 0.6 adjacent platform (Fig. 2). The readings of each element divided by the Ca intensity were recorded along the core-edge profile of each otolith, and a 5-order moving average was adjusted to attenuate the signal fluctuations. This process allows a better visualization of the standards.

A discriminant function analysis (DFA) on the Sr:Ca and Ba:Ca ratios were applied to the last 20 measurements average of each otolith from all individuals of the coastal areas to ascertain the adherence of the samples to one of the three suggested patterns of habitat use: 1) Marine Migrant (MM), i.e., fish in which the otolith Sr:Ca ratios were maintained at low levels (< 0.6) at the core and show a single increase to over 0.6 towards the otolith edges; 2) Estuarine Visitor (EV), i.e., fish in which the Sr:Ca ratios oscillate more than once between the estuarine (0.2–0.6) and marine (> 0.6) ratios; and 3) Nearshore Resident (NR), i.e., those fish with Sr:Ca ratios typical of being close to estuarine areas (0.4–0.6). The accuracy of this classification was assessed by the percentage of correctly classified individuals in the *leave one out* routine of the discriminant analysis. A one-way ANOVA test followed by a post-hoc Tukey test was used for comparisons of the elemental ratios among

the three movement patterns. We performed the Levene test for assessing homogeneity of variance and the Shapiro-Wilks W test for normality, previously to Discriminant and ANOVA analyses. The data reached the assumptions of homoscedasticity, but the normality was not accomplished in all cases. However, we used these parametric analyses, since violations of the normality assumption are usually not "fatal," meaning that the resultant significance tests are trustworthy (Klecka, 1980; Tabachnick and Fidell, 1996).

3. Results

Individuals from the estuarine systems ranged between 7.3 and 32 cm in total length, and those from the coastal region ranged from 28.5 to 66 cm in total length (Table 2), being classified as juveniles, subadults and adults. The fish examined from Bay 1 were juveniles, subadults and adults, and those from the coastal lagoon were juveniles and subadults, whereas the fish from Bay 2 were only subadults. The ages ranged from 0 to 9 years in the estuarine systems, with an average of 2.5 annuli, whereas in the coastal systems, the ages ranged between 1 and 22 annuli with an average of 6 annuli.

3.1. Estuarine systems

Overall, 32% of all juveniles appeared to remain within the estuarine range (Sr:Ca ratios from 0.2 to 0.6), particularly those from the Bay 1 (50%). Fish from the Coastal Lagoon (73%) remained very close to the boundary of the strip between estuaries and the adjacent platform bands, or even above this limit (Fig. 3; Supplementary Data, Figs. S1–S3).

The subadults that were recorded in the bays had chemical profiles that suggest permanence in estuarine areas (55%, the younger ones), whereas others (45%, the older ones) had profile ranges oscillating between the adjacent platform and estuarine bands after the formation of the first annual ring. All the subadults from the coastal lagoon had profiles between the estuarine and adjacent platform bands. The occurrences of adjacent platform bands were recorded earlier in individuals from Bay 2 than those from Bay 1 (Fig. 3; Supplementary Data, Figs. S1–S2). The adults from the Bay 1 had an oscillatory profile
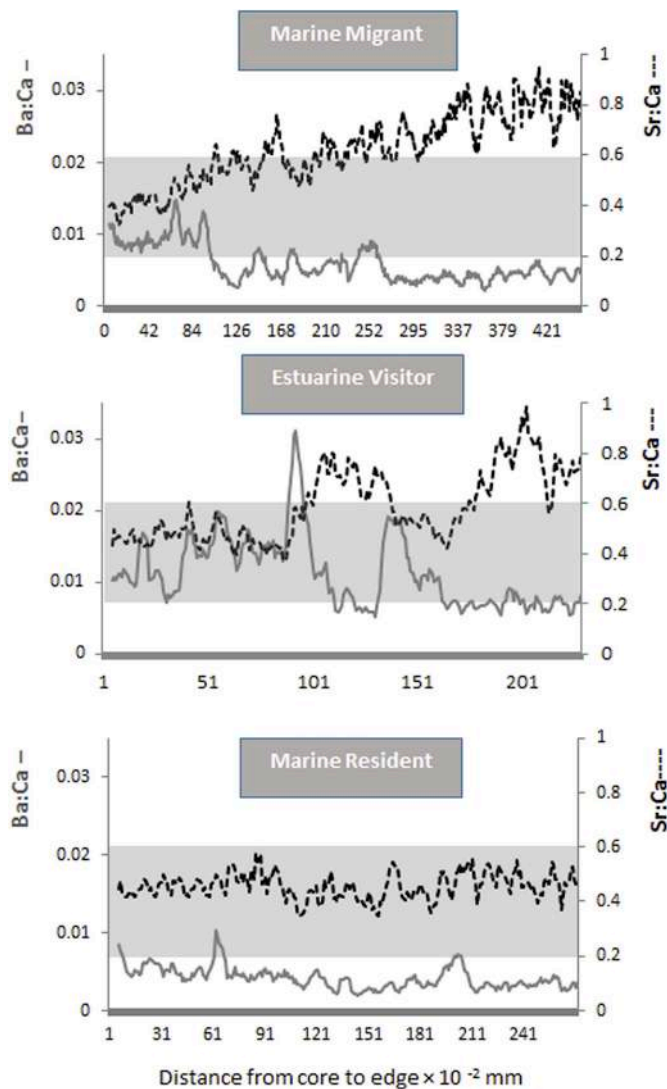
Fig. 4. Types of profiles for the Sr:Ca and Ba:Ca ratios in otoliths of adult individuals from the coastal areas. A. Marine Migrant. Specimen from Coastal Area 6, measuring 59.5 cm TL; B. Estuarine Visitor. Specimen from Coastal Area 2, measuring 33 cm TL; C. Nearshore Resident. Specimen from Coastal Area 6, measuring 48.5 cm of TL.
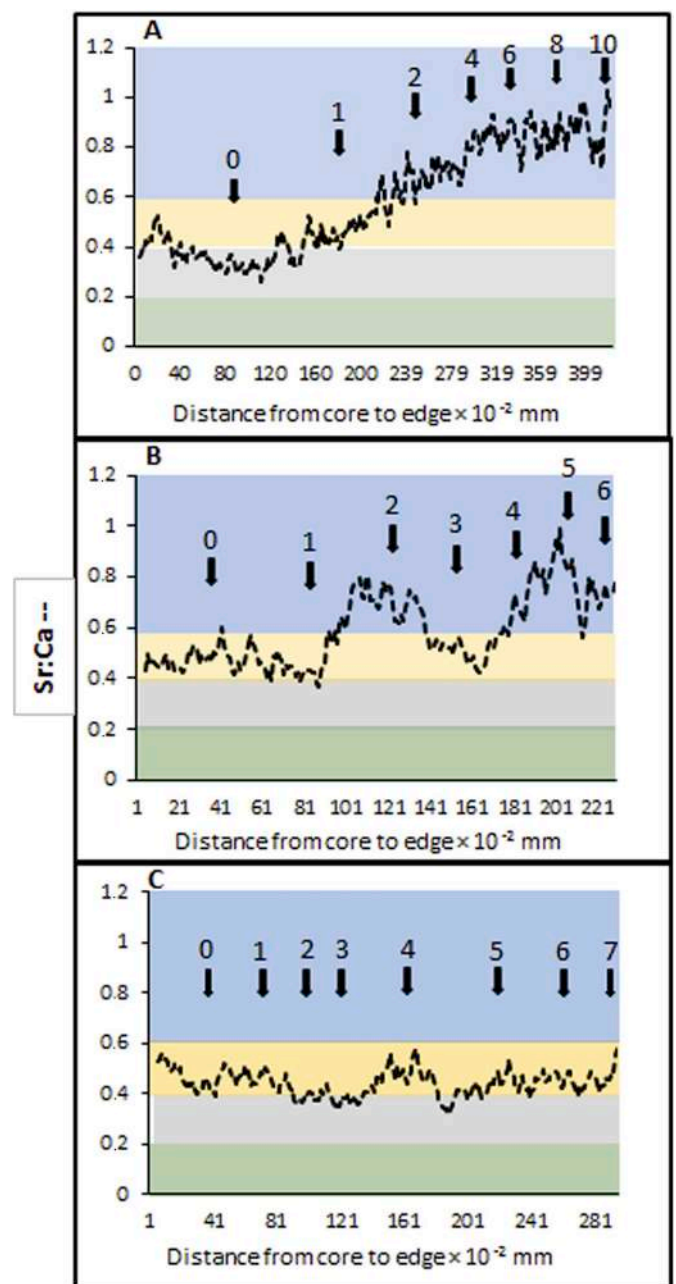

Fig. 5. Types of profiles for the Sr:Ca ratios in otoliths of adult individuals from the coastal area. A. Marine Migrant. Specimen from Coastal Area 6, measuring 47 cm TL; B. Estuarine Visitor. Individual from Coastal Area 2, measuring 33 cm TL; C. Nearshore Resident. Specimen from Coastal Area 9, measuring 51 cm TL. The arrows indicate the approximate annuli ring positions.

between the estuarine and the adjacent platform bands in all the ten cases.

3.2. Coastal areas

The patterns formed by the Sr:Ca and Ba:Ca ratios together (Fig. 4) showed an agreement for most cases (76%), although the Ba:Ca ratios have more unstable patterns with greater oscillation than the Sr:Ca ratios. Therefore, we opted not to delimit the use bands according to the Ba:Ca.

Three patterns of movements were found in individuals from the coastal areas according to the Sr:Ca ratios (Supplementary Data, Fig. S4). The individuals of the first pattern (Fig. 5 - A), assigned as Marine Migrants (MM), had the Sr:Ca ratios increasing more consistently after the formation of the first annual ring. The individuals with the second pattern (Fig. 5 - B), assigned as Estuarine Visitors (EV) presented oscillations between the estuarine and marine bands. A third pattern (Fig. 5 - C), named Nearshore Resident (NR), showed no indication of movements between marine areas and estuarine systems.

Fish classified as estuarine visitors were the most frequent, accounting for 59% of all individuals. They were particularly common in CA4 (81%), CA1 (74%) and CA2 (70%). Nearshore Residents were more abundant in CA8 (100%) and CA7 (57%), whereas the Marine Migrant pattern was more common in individuals of CA7 (54%) (Table 3). The Sr:Ca ratios were greater for the MM pattern, for both the core ($F_{2, 133} = 4.35$, $p = 0.01$) and the otolith edge only ($F_{2, 133} = 59.7$, $p < 0.01$) compared with the two other patterns, according to ANOVA and the post-hoc Tukey test.

The discriminant function analysis (DFA) correctly assigned the individuals to recognized patterns with accuracies of 87.5% to Marine Migrant, 59.0% to Estuarine Visitor and 78.6% to Nearshore Resident

Table 3

Percent of individuals of *Micropogonias furnieri* with each pattern of movements (MM, marine Migrant; EV, Estuarine Visitor; and NR, Neashore Resident) in the coastal areas of the Rio de Janeiro State according to the Sr:Ca ratios in otoliths. n, number of individuals. Coastal areas (1,2, 3… 9) described in the "Study area" section.

Coastal Area	n	MM	EV	NR
1	19	26% (5)	74% (14)	–
2	10	–	70% (7)	30% (3)
3	9	–	56% (5)	44% (4)
4	31	3% (1)	81% (24)	16% (5)
5	28	11% (3)	56% (16)	33% (9)
6	13	54% (7)	31% (4)	15% (2)
7	7	–	43% (3)	57% (4)
8	12	–	–	100% (12)
9	7	–	62% (5)	38% (3)
Total N	136	16	78	42
Total %	100%	12%	57%	31%

(Table 4). The plot of the first two axes of the DFA showed a clear separation between Marine Migrants and Nearshore Residents. The separation between Estuarine Visitors and the other two patterns was weak but still significant. (Fig. 6).

Table 4

Classification matrix of the DFA patterns of displacement of *Micropogonias furnieri*. The percentages in rows represent the classification of each group given in columns. MM, Marine Migrants; EV, Estuarine Residents; NR, Nearshore Residents; n, sample size.

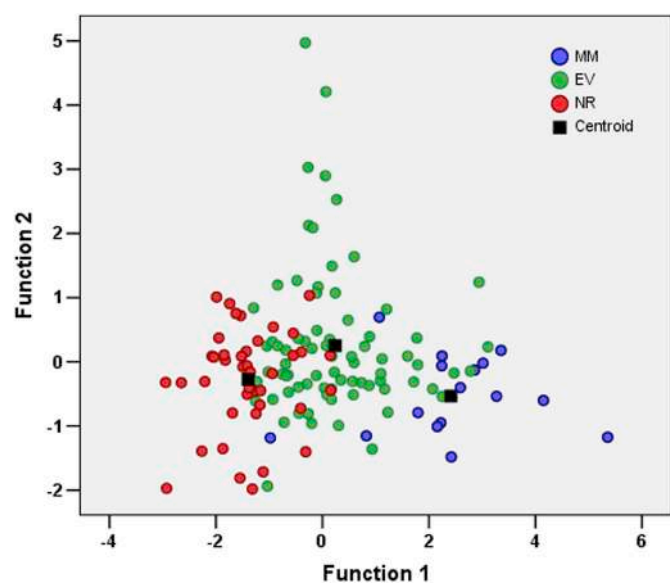|		MM	EV	NR	Total
N	MM	14	1	1	16
	EV	14	46	8	78
	NR	0	9	33	42
%	MM	87.5	6.3	6.3	100
	EV	17.9	59.0	23.1	100
	NR	0.0	21.4	78.6	100

Fig. 6. Ordination diagram of the two first axes of the discriminant function analysis on the Sr:Ca and Ba:Ca ratios, with the samples coded by the three movement patterns (MM, Marine Migrant; EV, Estuarine Visitor; NR, Nearshore Resident).

4. Discussion

Three movement patterns were suggested based on Sr:Ca lifelong profiles in otoliths of *M. furnieri*, thus indicating the presence of individual variability in habitat use along the sampled area. Estuarine Visitors represented the most frequent pattern of habitat use (57% of all coastal fish) and refer to marine individuals who periodically return to the estuaries. Otoliths of Estuarine Visitors showed Sr:Ca and Ba:Ca profiles varying in opposite directions, alternating marine and estuarine signals throughout fish growth, thus suggesting that some adult fish return sporadically to estuaries. The reason for this visit to estuaries, however, is not completely understood, but reproduction and feeding (Vieira et al., 1998; Mendoza-Carranza and Vieira, 2007) have been suggested as potential reasons. In addition, this profile may not indicate an actual entrance into the estuaries but the use of the adjacent platform close to an estuarine connection with marked estuarine influence. In this case, the adults would remain long enough under this influence to incorporate intensity typical of estuarine areas.

Nearshore Resident fish (31% of all coastal fish) showed constant Sr:Ca ratios along the otolith growth axis, as they have been captured in nearshore areas near to estuarine influences. This chemical characteristic can be explained by individuals who do not enter estuaries in the juvenile phase as expected. The entrance into the estuarine systems by individuals in the initial phase of the life cycle usually occurs in a passive way, through the transport of eggs and larvae in currents of tides and winds (Vieira et al., 1998; Costa and Araújo, 2003). The Nearshore Residence or absence of the migration phenomenon could be associated with low individual energetic availability, directing reproduction instead of migration between estuarine areas and the adjacent platform, thus avoiding expenses with osmoregulation (Chapman et al., 2012). Thus, a population contingent could recruit in alternative areas to coastal systems, such as oceanic beaches (Brown and McLachlan, 1990). Exposed beaches offer shelter for young fish due to their low depth and high dynamism, and food availability (e.g., zooplankton and benthic organisms) (Ayvazian and Hyndes, 1995; Beyst et al., 2002; Rodrigues and Vieira, 2012). Because of this, these beaches play an important role as rearing grounds for fish species. Individuals in the juvenile stages of *M. furnieri* are frequently included in lists of fish species in surf zones of exposed beaches along the southern and southeastern Brazilian coast (Monteiro-Neto et al., 1995; Pereira et al., 2014; Azevedo et al., 2017; Araújo et al., 2018).

Marine Migrants (12% of all coastal fish) corresponded to fish that go through early development inside estuaries, and after one or two years, they eventually migrate to the coast. This movement towards the adjacent platform would represent an important step in completing the life cycle (Vieira et al., 1998). However, the presence of nearshore residents suggests that this migration towards adjacent platforms is not obligatory with a contingent of this population staying in coastal nearshore areas next to estuarine influences. Many studies on size structure have been carried out for this species along the Brazilian coast, indicating movements of fish leaving the estuarine areas towards the continental shelf after its early life stage, as reported along the Brazilian southeastern (Costa and Araújo, 2003) and southern (Vazzoler, 1991; Cavole and Haimovici, 2015) coasts. The main reason for this movement could be associated with salinity stability that would allow the fish to save energy with osmoregulation, rather allocating it to other processes, such as growth and reproduction (Cavole and Haimovici, 2015). However, there is need for further studies to clarify this hypothesis.

The narrow connection of certain systems may act as a barrier to entry back into the estuarine system for adult individuals. The MM profile was more common in the CA6, where the nearest estuarine system has a very narrow connection with the sea when compared to the bays that had the highest EV occurrences. At the same time, a narrowly connected lagoon probably does not influence the water bodies of the adjacent coastal zone in the same way as the large bays

and estuaries, with individuals of such areas having chemical characteristics similar to those from the adjacent platform. The NR patterns were the most represented in CA3 and CA8, inshore areas influenced by the continental water bodies of Guanabara Bay and Paraíba do Sul River Estuary, respectively. Therefore, individuals approaching these systems would not be sufficiently exposed to different chemical characteristics of the adjacent platform to the point of being detected in the otoliths.

Our findings corroborate the theory of partial migration (Chapman et al., 2012), which states that a population contingent migrates whereas another contingent remains a resident in a given area. The factors influencing such divergence may be associated with environmental constraints or ecological interactions experienced by each individual fish, such as physiological tolerance and intraspecific competition (Chapman et al., 2012). In the case of *M. furnieri*, physical constraints for a return to estuarine areas should be taking into account when opting to stay in a given area or migrate. The body size may also be an ecological driver of partial migration. In this case, this feature would be a physiological variation with trade-offs associated with reproductive and feeding processes. Individuals of *M. furnieri* may move within the estuarine areas according to their ontogenetic development. They enter the estuaries as eggs and larvae (< 3 cm) and seek shallow areas in the inner protected zones. As they grow, they seek deeper waters within these systems, which may indicate the beginning of the migration to the adjacent platform. The timing of migration may be associated with the first sexual maturation, after reaching approximately 15 cm of total length in southern (latitude 32° S, Cavole and Haimovici, 2015) and 20 cm in the southeastern (23° S, Costa and Araújo, 2003) Brazil.

Individuals collected in bays and coastal lagoons such as those studied in the estuarine systems had slight variations in their otolith microchemistries. In general, all presented a pattern of Sr increases along the core-edge profile, and most individuals remained within the expected values for estuarine environments until the formation of the first or second annual ring. These increases in Sr:Ca may be related to the movements from shallower and more internal areas of the estuarine zones, where they spend more time as juveniles, to deeper areas in the outer estuarine zones next to the sea connection but still within the estuarine system (González-Sansón et al., 1996). These internal movements were observed in the estuary of the River Plate (Uruguay) as indicated in studies of distribution by age classes with the largest individuals found more in deep areas with comparatively higher salinity (Jaureguizar et al., 2003, 2008). In the Sepetiba Bay, fish with different ages were analysed, which seemed to confirm the EV pattern in adult individuals. These movements were also identified in a study of size structure performed by Costa and Araújo (2003). They associated these movements with the search for more energetically profitable foods in the marine environment and the lower risk of predation until they reached adulthood. In the coastal lagoon (Araruama lagoon), the individuals' profiles were much closer to the border between estuarine and adjacent platform profiles, reaching the marine band when still very young, which appears to be a result of the hypersaline conditions in parts of the lagoon and do not reflect the exit to the marine environment. The study is a step to better understanding the plasticity in habitat use for different population contingents of a very important fishery resource along the southwestern Atlantic coast. The diversity of movement profiles found may indicate a great resilience of *M. furnieri* in cases of environmental disturbance (Costa et al., 2015). Therefore, the existence of different life cycle strategies and movement patterns may ensure that this species has a decreased chance to undergo deleterious events.

Funding

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed, including Universidade Federal Rural do Rio de Janeiro, Brazil, Animal Care Protocol (# 11874).

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2018.11.015.

References

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.

Albuquerque, C.Q., Miekeley, N., Muelbert, J.H., Walther, B.D., Jaureguizar, A.J., 2012. Estuarine dependency in a marine fish evaluated with otolith chemistry. Mar. Biol. 159 (10), 2229–2239.

Araújo, F.G., Pinto, S.M., Neves, L.M., Azevedo, M.C.C., 2016. Inter-annual changes in fish communities of a tropical bay in southeastern Brazil: what can be inferred from anthropogenic activities? Mar. Pollut. Bull. 114 (1), 102–113. https://doi.org/10.1016/j.marpolbul.2016.08.063.

Araújo, F.G., Teixeira, T.P., Guedes, A.P.P., Azevedo, M.C.C., Pessanha, A.L.M., 2018. Shifts in the abundance and distribution of shallow water fish fauna on the southeastern Brazilian coast: a response to climate change. Hydrobiologia 810, 205–218.

Avigliano, E., Velasco, G., Volpedo, A.V., 2015. Assessing the use of two southwestern Atlantic estuaries by different life cycle stages of the anadromous catfish *Genidens barbus* (Lacépède, 1803) as revealed by Sr:Ca and Ba:Ca ratios in otoliths. J. Appl. Ichthyol. 31, 740–743.

Avigliano, E., Domanico, A., Sánchez, S., Volpedo, A.V., 2017. Otolith elemental fingerprint and scale and otolith morphometry in *Prochilodus lineatus* provide identification of natal nurseries. Fish. Res. 186, 1–10. https://doi.org/10.1016/j.fishres.2016.07.026.

Avigliano, E., Pisonero, J., Dománico, A., Silva, N., Sánches, S., Volpedo, A.V., 2018. Spatial segregation and connectivity in Young and adult stages of *Megaleporinus obtusidens* inferred from otolith elemental signatures: implication for management. Fish. Res. 204, 239–244.

Ayvazian, S.G., Hyndes, G.A., 1995. Surf-zone fish assemblages in south-western Australia: do adjacent nearshore habitats and the warm Leeuwin Current influence the characteristics of the fish fauna? Mar. Biol. 122, 527–536.

Azevedo, M.C.C., Gomes-Gonçalves, R.S., Mattos, T.M., Uehara, W., Guedes, G.H.S., Araújo, F.G., 2017. Taxonomic and functional distinctness of the fish assemblages in three coastal environments (bays, coastal lagoons and oceanic beaches) in Southeastern Brazil. Mar. Environ. Res. 129, 180–188.

Beyst, B., Hostens, K., Mees, J., 2002. Factors influencing the spatial variation in fish and macrocrustacean communities in the surf zone of sandy beaches in Belgium. J. Mar. Biol. Assoc. U. K. 82, 181–187.

Bradbury, I., DiBacco, C., Thorrold, S.R., Snelgrove, P.V.R., Campana, S.E., 2011. Resolving natural tags using otolith geochemistry in an estuarine fish, raibow smelt *Osmerus mordax*. Mar. Ecol. Prog. Ser. 433, 195–204.

Brown, A.C., McLachalan, A., 1990. Ecology of Sandy Shores. Elservier, Amsterdam 327p.

Brown, R.J., Severin, K.P., 2009. Otolith chemistry analyses indicate that water Sr:Ca is the primary factor influencing otolith Sr:Ca for freshwater and diadromous fish but not for marine fish. Can. J. Fish. Aquat. Sci. 66, 1790–1808. https://doi.org/10.1139/F09-112.

Callicó Fortunato, R.7., Benedito Durà, V., Volpedo, A., 2017. Otolith morphometry and microchemistry as habitat markers for juvenile *Mugil cephalus* (Linnaeus 1758) in nursery grounds in the Valencian community, Spain. J. Appl. Ichthyol. 33 (2), 163–167. https://doi.org/10.1111/jai.13291.

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

Castello, J.P., 1986. Distribución, crecimiento y maduración sexual de la corvina juvenil (*Micropogonias furnieri*) en el estuario de la "Lagoa dos Patos", Brasil. Physis 44, 21–36.

Cavole, L.M., Haimovici, M., 2015. The use of otolith microstructure in resolving issues of ageing and growth of young *Micropogonias furnieri* from southern Brazil. Mar. Biol. Res. 11 (9), 933–943.

Chang, C.W., Iizuka, Y., Tzeng, W.N., 2004. Migratory environmental history of the grey mullet *Mugil cephalus* as revealed by otolith Sr:Ca ratios. Mar. Ecol. Prog. Ser. 269, 277–288.

Chapman, B.B., Hulthén, K., Brodersen, J., Nilson, P.A., Skov, C., Hansson, L.A., Bronmark, C., 2012. Partial migration in fishes: cause and consequences. J. Fish. Biol. 81, 456–478.

Condini, M., Tanner, S., Reis-Santos, P., Albuquerque, C., Saint'Pierre, T., Vieira, J., Garcia, A., 2016. Prolonged estuarine habitat use by dusky grouper *Epinephelus marginatus* at subtropical latitudes revealed by otolith microchemistry. Endanger. Species Res. 29 (3), 271–277.

Costa, M.D.P., Muelbert, J.H., Vieira, J.P., Castello, J.P., 2015. Dealing with temporal variation and different life stages of whitemouth croaker *Micropogonias furnieri* (Actinopterygii, Sciaenidae) in species distribution modeling to improve essential estuarine fish habitat identification. Hydrobiologia 762 (1), 195–208.

Costa, M.R., Araújo, F.G., 2003. Use of a tropical bay in southeastern Brazil by juvenile and subadult *Micropogonias furnieri* (Perciformes. Sciaenidae). ICES J. Mar. Sci. 60 (2), 268–277. https://doi.org/10.1016/S1054-3139(02)00272-2.

Costa, M.R., Pereira, H.H., Neves, L.M., Araújo, F.G., 2013. Length-weight relationships of 23 fish species from Southeastern Brazil. J. Appl. Ichthyol. 30, 230–232.

D'anatro, A., Pereira, A.N., Lessa, E.P., 2011. Genetic structure of the white croaker. *Micropogonias furnieri* Desmarest 1823 (Perciformes: Sciaenidae) along Uruguayan coasts: contrasting marine, estuarine and lacustrine populations. Environ. Biol. Fish. 91 (4), 407–420.

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, 1796–1810.

Davoren, G., Halden, N., 2014. Connectivity of capelin (*Mallotus villosus*) between regions and spawning habitats in Newfoundland inferred from otolith chemistry. Fish. Res. 159, 95–104.

Diaz, A.O., García, A.M., Figueroa, D.E., Goldemberg, A.L., 2008. The mucosa of the digestive tract in *Micropogonias furnieri*: a light and electron microscope approach. Anat. Histol. Embryol. 37, 251–256.

Elsdon, T.S., Gillanders, B.M., 2005. Consistency of patterns between laboratory experiments and field collected fish in otolith chemistry: an example and applications for salinity reconstructions. Mar. Freshw. Res. 56, 609–617. https://doi.org/10.1071/MF04146.

Froese, R., Pauly, D., 2017. World wide Web electronic publication. http://www.fishbase.org, Accessed date: 10 December 2017.

González-Sansón, G., Bosch, Méndez A., Guevara Carrió, E., Aguilar, C.B., 1996. Composición por tallas de las capturas de la corvina *Micropogonias furnieri* (Desmarest. 1823) (Osteichthyes: Sciaenidae) en la Bahia de Cienfuegos Cuba. Rev. Invest. Mar. 17, 189–195.

Jaureguizar, A.J., Bava, J., Carozza, C.R., Lasta, C.A., 2003. Distribution of whitemouth croaker *Micropogonias furnieri* in relation to environmental factors at the Río de la Plata estuary, South America. Mar. Ecol. Prog. Ser. 255, 271–282.

Jaureguizar, A.J., Militelli, M.I., Guerrero, R.A., 2008. Environmental influence on maturity stage spatial distribution of whitemouth croaker (*Micropogonias furnieri*) along an estuarine gradient. J. Mar. Biol. Assoc. U. K. 88, 175–181.

Kjerfve, B., 1994. In: In: Kjerfve, B. (Ed.), Coastal Lagoon Processes ed 60 Elservier Oceanografy Series, Amsterdam.

Kjerfve, B., Ribeiro, C.H.A., Dias, G.M., Filippo, A.M., Quaresma, V.S., 1997. Oceanographic characteristics of an impacted coastal bay: Baia de Guanabara, Rio de Janeiro, Brazil. Continent. Shelf Res. 17 (13), 1609–1643.

Klecka, W.R., 1980. Discriminant Analysis. Quantitative Applications in the Social Sciences. Series 19. Sage Publications, Thousand Oaks, CA.

Macchi, G.J., Acha, M.E., Lasta, C.A., 1996. Desove y fecundidad de la corvina rubia *Micropogonias furnieri* Desmarest, 1823 del estuario del Río de la Plata, Argentina. Boletín. Instituto Español de Oceanografía 12 (2), 99–113.

Mai, A.C.G., Santos, M.L., Lemos, V.M., Vieira, J.P., 2018. Discrimination of habitat use between two sympatric species of mullets, *Mugil curema* and *Mugil liza* (Mugiliformes: Mugilidae) in the rio Tramandaí Estuary, determined by otolith chemistry. Neotrop.

Ichthyol. 16 (2), e170045. https://doi.org/10.1590/1982-0224-20170045.

McCulloch, M.T., Cappo, M., Aumend, J., Müller, W., 2005. Tracing the life history of individual barramundi using laser ablation MC-ICP-MS Sr-isotopic and Sr/Ba ratios in otoliths. Mar. Freshw. Res. 56 (5), 637–644. https://doi.org/10.1071/MF04184.

Mendoza-Carranza, M., Vierira, J.P., 2007. Whitemouth croaker *Micropogonias furnieri* (Desmarest, 1823) feeding strategies across four southern Brazilian estuaries. Aquat. Ecol. 42 (1), 83–93. https://doi.org/10.1007/s10452-007-9084-4.

Miller, J.A., 2011. Effects of water temperature and barium concentration on otolith composition along a salinity gradient: implications for migratory reconstructions. J. Exp. Mar. Biol. Ecol. 405, 42–52. https://doi.org/10.1016/j.jembe.2011.05.017.

Monteiro-Neto, C., Helmer, J.L., Teixeira, R.L., Musick, J.A., 1995. Food habits of young *Trachinotus* spp. in the inner surf zone of a sandy beach in SE Brazil. Atlantica 17, 95–107.

Morales-Nin, B., Geffen, A.J., Pérez-Mayol, S., Palmer, M., González-Quirós, R., Grau, A., 2012. Seasonal and ontogenic migrations of meagre (*Argyrosomus regius*) determined by otolith geochemical signatures. Fish. Res. 127–128, 154–165. https://doi.org/10.1016/j.fishres.2012.02.012.

Pereira, H.H., Neves, L.M., Costa, M.R., Araújo, F.G., 2014. Fish assemblage structure on sandy beaches with different anthropogenic influences and proximity of spawning grounds. Mar. Ecol. 36, 16–27.

Rodrigues, F.L., Vieira, J.P., 2012. Surf zone fish abundance and diversity at two sandy beaches separated by long rocky jetties. J. Mar. Biol. Assoc. U. K. 93 (4), 867–875.

Santos, R.S., Costa, M.R., Araújo, F.G., 2017. Age and growth white croaker *Micropogonias furnieri* (Perciformes, Sciaenidae) in coastal area of southeastern Brazilian Bight. Neotrop. Ichthyol. 15 (1), e160131.

Schindler, D.E., Hilborn, R., Chasco, B., Boatright, C.P., Quinn, T.P., Rogers, L.A., Webster, M.S., 2010. Population diversity and the portfolio effect in an exploited species. Nature 465, 609–612.

Schwingel, P.R., Castello, J.P., 1990. Validacion de la edad y crecimiento de la corvina (*Micropogonias furnieri*) em el sur de Brasil. Frente Maritimo 7, 19–24.

Secor, D.H., 1999. Specifying divergent migrations in the concept of stock: the contingent hypothesis. Fish. Res. 43 (1–3), 13–34.

Secor, D.H., Piccoli, P., 2007. Determination of frequency of anadromous migrations by Chesapeake Bay striped bass based upon otolith microchemical analysis. Fish. Bull. 105, 62–73.

Secor, D.H., Rooker, J.R., 2000. Is otolith strontium a useful scalar of life cycles in estuarine fishes? Fish. Res. 46, 359–371. https://doi.org/10.1016/S0165-7836(00)00159-4.

Silvano, R.A.M., MacCord, P.F.L., Lima, R.V.A., Begossi, A., 2006. When does this fish spawn? Fishermen's local knowledge of migration and reproduction of Brazilian coastal fishes. Environ. Biol. Fish. 76, 371–386. https://doi.org/10.1007/s10641-006-9043-2.

Sturrock, A.M., Trueman, C.N., Darnaude, A.M., Hunter, E., 2012. Can otolith elemental chemistry retrospectively track migrations in fully marine fishes? J. Fish. Biol. 81, 766–795. https://doi.org/10.1111/j.1095-8649.2012.03372.x.

Tabachnick, B.G., Fidell, L.S., 1996. Using Multivariate Statistics. Harper Collins College Publishers, New York.

Tanner, S.E., Reis-Santos, P., Vasconcelos, R.P., Fonseca, V.F., França, S., Cabral, H.N., Thorrold, S.R., 2013. Does otolith geochemistry record environmental conditions in a temperate tidal estuary? J. Exp. Mar. Biol. Ecol. 441, 7–15.

Tulp, I., Keller, M., Navez, J., Winter, H.V., Graaf, M., Baeyens, W., 2013. Connectivity between migrating and landlocked population of a diadromous fish species investigated using otolith microquemistry. PloS One 8, e69796.

Vazzoler, A.E.A.M., 1991. Síntese de conhecimentos sobre a biología da corvina. *Micropogonias furnieri* (Demarest. 1823) da costa do Brasil. Atlântica 13, 55–74.

Vieira, J.P., Castello, J.P., Pereira, L.E., 1998. A ictiofauna. In: Seeliger, U., Odebrecht, C., Castello, J.P. (Eds.), Os ecossistemas costeiro e marinho do extremo sul do Brasil. Rio Grande, Ed. Ecoscientia, pp. 60–68.

Vizziano, D., Forni, F., Saona, G., Norbis, W., 2002. Reproduction of *Micropogonias funieri* in a shallow temperate coastal lagoon in the southern Atlantic. J. Fish. Biol. 61, 196–206.

Volpedo, A.V., Cirelli, A.F., 2006. Otolith chemical composition as a useful tool for sciaenid stock discrimination in the south-western Atlantic. Sci. Mar. 70, 325–334 ISSN: 0214-8358.

Walsh, C.T., Gillanders, B.M., 2018. Extrinsic factors affecting otolith chemistry - implications for interpreting migration patterns in a diadromous fish. Environ. Biol. Fish. 101 (6), 905–916. https://doi.org/10.1007/s10641-018-0746-y.

Walther, B.D., Limburg, K.E., 2012. The use of otolith chemistry to characterize diadromous migrations. J. Fish. Biol. 81, 796–825. https://doi.org/10.1111/j.1095-8649.2012.03371.x.

Walther, B.D., Thorrold, S.R., 2006. Water, not food, contributes de majority of strontium and barium deposited in the otoliths of a marine fish. Mar. Ecol. Prog. Ser. 311, 125–130.