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Original article

Relationships between fish and otolith dimensions of *Pomatomus saltatrix* (Linnaeus, 1766) (Perciformes: Pomatomidae) in southeastern Brazil

Geysa M. de Souza[1,3], Rafael de A. Tubino[2], Cassiano Monteiro-Neto[1,3] and Marcus R. da Costa[1,3]

The bluefish, *Pomatomus saltatrix* (Linnaeus, 1766), was used as a species-specific model to study morphometric relationships between otolith size and relative growth variables. Length-weight relationships between Otolith (Length-OL, Height-OH, and Weight-OW) and fish measurements (Total Length-TL and Total Weight-TW) were determined for fishes captured monthly during the year 2015 off the southeastern coast of Brazil. The ANCOVA and Kruskal-Wallis analysis did not indicate significant differences in the relative growth constants between sexes and length frequency distributions ($p > 0.05$). The condition factor also did not present significant differences between sexes, and right and left otolith measurements ($p > 0.05$). A total of 398 specimens were sampled: TL = 43.6-67.0 cm, TW = 365-2400 g, OL = 9.65-15.25 mm, OH = 3.65 - 5.45 mm and OW = 0.03-0.11 g. The LWR for grouped sexes was $TW = 0.050TL^{2.55}$ and otoliths $OW = 6.17E\text{-}05OL^{2.59}$. The best adjustments were TL *vs* OL ($r^2 = 0.90$); OL *vs* OW ($r^2 = 0.90$); TW *vs* OW ($r^2 = 0.81$); and TW *vs* OL ($r^2 = 0.80$). These results showed that such relationships are helpful tools for predicting the fish size and weight from otoliths, which may be used in food habits and paleontology studies, and other fisheries management applications.

Keywords: Bluefish, LWR, Otolith morphometrics, *Sagitta* otolith, Somatic growth.

A anchova, *Pomatomus saltatrix* (Linnaeus, 1766), foi usada como modelo espécie-específico de relações morfométricas de otólitos e variáveis de crescimento relativo. As relações peso-comprimento entre otólito (comprimento-CO, altura-AO e peso-PO) e tamanho do peixe (comprimento total-CT e peso total-PT) foram determinadas para indivíduos capturados mensalmente durante o ano de 2015 na costa sudeste do Brasil. As análises de ANCOVA e Kruskal-Wallis não indicaram diferenças significativas para as constantes de crescimento relativo entre os sexos e distribuições de frequência de comprimento ($p > 0,05$). O fator de condição também não apresentou diferenças significativas entre os sexos, e medidas do otólito direito e esquerdo ($p > 0,05$). Um total de 398 espécimes foram amostrados: CT = 43,6-67,0 cm e PT = 365-2400 g. A RPC para peixes foi $PT = 0.050CT^{2,55}$ e para os seus otólitos foi $PO = 6.17E\text{-}05CO^{2,59}$, CO = 9.65-15.25 mm, AO = 3.65 - 5.45 mm and PO = 0.03-0.11 g. Os melhores ajustes foram observados para CT *vs* CO ($r^2 = 0,90$); CO *vs* PO ($r^2 = 0,90$); PT *vs* PO ($r^2 = 0,81$) e PT *vs* CO ($r^2 = 0,80$). Os resultados mostraram que essas relações são ferramentas úteis na geração de estimativas de tamanho e peso dos peixes a partir dos otólitos, permitindo a sua aplicação em estudos em outras áreas, incluindo hábitos alimentares, paleontologia e manejo da pesca.

Palavras-chave: Anchova, Crescimento somático, Morfometria de otólitos, Otólitos *sagitta*, RPC.

Introduction

Fish otoliths are useful anatomical parts in several life history and ecological studies (Volpedo, Vaz dos Santos, 2015). Otoliths are metabolically inert, grow during the entire life cycle (Ferguson *et al*., 2011), and may be considered as permanent recorders of the environment on their Aragonite matrix. Animals are exposed to a combination of elements that are unique of their surroundings, with otoliths functioning as phenotypic markers (Panfili *et al*., 2002).

Otolith size and shape vary among species and individuals (Eroğlu, Şen, 2009), and may be used for morphometric analyzes. Aguilera *et al.* (2013) used otoliths for paleontological identification of fossil fishes, and Tuset *et al.* (2008)

[1]Laboratório de Biologia do Nécton e Ecologia Pesqueira, Departamento de Biologia Marinha, Universidade Federal Fluminense, Outeiro de São João Batista s/n, 24020-971 Niterói, RJ, Brazil. geysa.marinho@hotmail.com, https://orcid.org/0000-0003-4462-0255 (Corresponding author)
[2]Departamento de Biologia Animal, Universidade Federal Rural do Rio de Janeiro, Rodovia BR 465, Km 7, 23890-000 Seropédica, RJ, Brazil. rattubino@gmail.com, https://orcid.org/0000-0002-3175-4724
[3]Programa de Pós-Graduação em Biologia Marinha, Departamento de Biologia Marinha, Universidade Federal Fluminense, Niterói, RJ, Brazil. (CMN) cmneto@id.uff.br, https://orcid.org/0000-0001-9342-8089, (MRC) marcusrc@id.uff.br, https://orcid.org/0000-0002-0737-1184

indicated their complementary use on stratigraphy, archaeology and zoogeography. Other applications include stock identification (Begg, Brown, 2000), and food habit studies (Tarkan *et al*., 2007). Additionally, otolith dimensions allow the back-calculationof fish size and biomass (Waessle *et al*., 2003), and weight to estimate age (Lepak *et al*., 2012). Also, otolith microchemistry composition provides chemical signalsthat may elucidate movements and migration patterns of fish stocks (Fraile *et al*., 2016).

Bluefish (*Pomatomus saltatrix*) is a marine pelagic migratory fish, found in continental shelf and estuarine waters of temperate and tropical regions (Juanes *et al*., 1996). The species is an active piscivorous fish (Haimovici, Krug, 1992), preyed by top predators such as sharks (Wood *et al*., 2009) and dolphins (Milmann *et al*., 2016). The bluefish is an important worldwide fishery resource captured by industrial, artisanal and recreational fisheries in the South Atlantic off the southeastern coast of Brazil (Haimovici, Krug, 1996; Lucena, O'Brien, 2005), in the North Atlantic along the coast of the United States (Buckel, Conover, 1997; Robillard *et al*., 2008), in eastern Australia (Zeller *et al*., 1996) and in the Mediterranean (Dhieb *et al*., 2005).

Several studies on the bluefish focused on age and growth (Krug, Haimovici, 1989; Robillard *et al.*, 2009), reproduction (Haimovici, Krug, 1992; Robillard *et al*., 2008), diet (Haimovici, Krug, 1992) and fisheries (Haimovici, Krug, 1996; Lucena, O'Brien, 2005). Nevertheless, studies on the morphometric relationships of bluefish otoliths are few and geographically limited in the literature (Hare, Cowen, 1995; Ceyhan, Akyol, 2006; Zengin *et al*., 2017; Bal *et al*., 2018). The aim of this paper was to provide information on the length-weight relationships (LWR) and condition factor (k) of bluefish, and the relationships between otolith dimensions and fish size, testing the hypothesis that such relations may provide useful predictive equations for estimating fish length and weight.

Material and Methods

Specimens of *P. saltatrix* were randomly collected from monthly commercial catches of gill net boats operating on the southeastern coast of Brazil (23º00'S, 44º00'W and 22º00'S, 41º00'W), landed in Niterói (RJ) between January and December 2015 (Fig.1).

All individuals were measured to the nearest 0.1 cm for total length (TL) and the total weight of each fish was recorded to the nearest 0.01 g. All TL values were distributed in size classes of 2 cm and the Kruskal-Wallis test was used to determine statistical differences in length frequency distributions between sexes. Sex was determined by macroscopic examination of the gonads (219♀, 174♂ and 5 unidentified) using a standard classification (Brown-Peterson *et al*., 2011). The pairs of *sagittal* otoliths were removed cleaned and stored in small, labeled envelopes. Otolith length (OL) was measured by a digital caliper rule (0.01 mm) and otolith weight (OW) with an electronic precision balance (Bioprecisa JA3003, 0.0001 g). OL was considered as the greatest distance between anterior and posterior edge, and OH as the

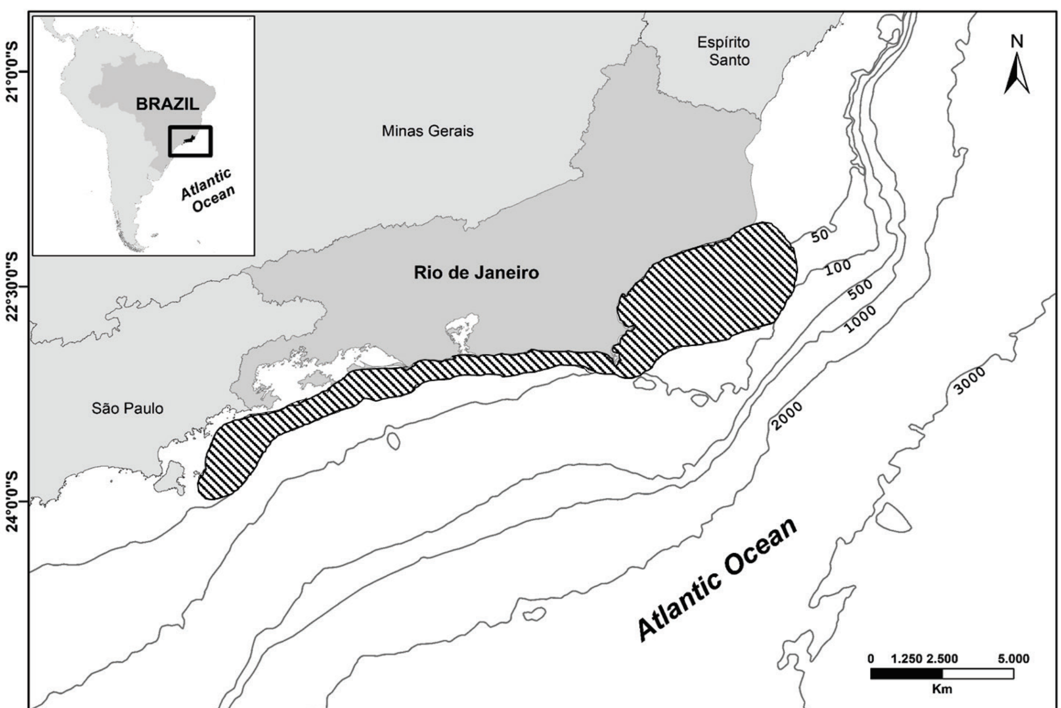

Fig. 1. Map of sampling area, hatched area identifies where catches of *Pomatomus saltatrix* occurred, off the Brazilian coast in the Southeastern Atlantic Ocean.

greatest distance from dorsal ventral edge (Fig. 2). A t-test was used to determine differences between left and right otoliths.

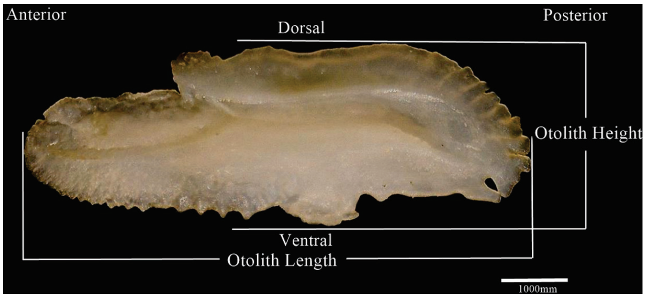

Fig. 2. Left sagitta otolith of *Pomatomus saltatrix*, with indicated measurements (TL = 57.9 cm, TW = 1817.0 g).

The LWR is expressed by the equation: $TW = a \times TL^b$, where TW is the body weight, TL is the total length, *a* and *b* are regression parameters. Parameters *a* and *b* were estimated by the converted logarithmic expression: $\log TW = \log a + b \log TL$, where *a* is the intercept of the regression curve (coefficient related to body form) and *b* the regression coefficient (exponent indicating isometric growth) (Froese, 2006). Additionally, the 95% confidence limits (CL) of *a* and *b* were estimated. Outliers observed in the log–log curves of all species were excluded from the regression. The difference between sexes for LWR was tested using analysis of covariance (ANCOVA). The hypothesis of isometric growth ($b = 3$) (Zar, 2010) was tested with the Student's t-test. We also estimated the condition factor, a quantitative parameter of the well-being of the fish, by the following expression: $k = TW / TL^b$, where k represents the condition factor and *b* the alometry coefficient, which is related with the form the individuals grow, and calculated from the length-weight relationship (Le-Cren, 1951). The analysis of variance (ANOVA) was applied to verify significant differences between sexes for the k values. The relationship between the otolith size (length-OL, height-OH, weight-OW) and fish size (total length-TL, total weight-TW) were determined using a power regression model between various measurements (Zar, 1984). The agreement between the models and the data was verified with the coefficient of determination (r^2). Statistical analyses were performed using Statistica™ (StatSoft Inc., 2007) and regression models compiled under Excel software (version 2007) for determining the relationships between fish size and otolith size. $P < 0.05$ was considered as the significance level.

Results

A total of 398 pairs of otoliths were collected and analyzed from specimens ranging between 43.6 cm and 67.0 cm TL (mean ± SD = 51.8 ± 5.30 cm), and 365.0 g to 2400.0 g TW (mean ± SD = 1182.4 ± 352.3 g). Within the collected samples only five specimens were not sexually identified (TL = 45.5 to 53.0 cm), the females (N = 219) ranging between 44.1 cm to 67.0 cm TL slightly prevailed over males (N = 174, 43.6 cm to 66.1 cm TL), and no significant difference was observed between size classes (Kruskal-Wallis, H = 13.52, $p = 0.332$). Regarding the size structure, approximately 50% of the specimens analyzed occurred between the classes of 44.0 and 48.0 cm TL (Fig. 3a), indicating that captured individuals were above the length of first sexual maturity and near the length limit where all individuals are sexually mature ($L_{50} = 40.0$ cm; $L_{100} = 45.0$ cm; Haimovici, Krug, 1992).

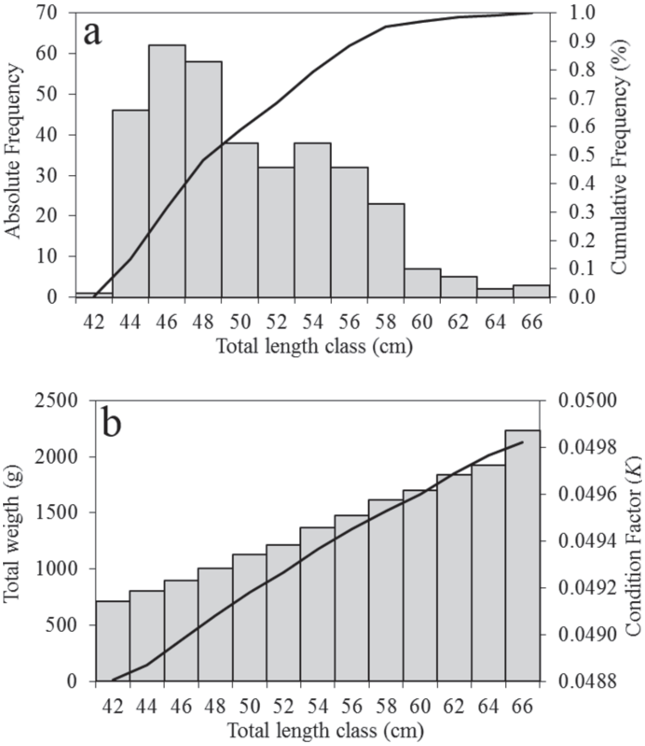

Fig. 3. Absolute and cumulative frequency of individuals by length class (cm) (a) and total weight of individuals by length class and condition factor (k) (b) of *Pomatomus saltatrix*, obtained from commercial catches off the Brazilian coast in the Southeastern Atlantic Ocean.

The covariance analysis (ANCOVA) applied to the parameters of the length-weight relationship for sexes was not significant (F = 2.791, df = 1, $p = 0.096$). The LWR equation for all individuals sampled was $TW = 0.050\ TL^{2.55}$ with the coefficient of determination $r^2 = 0.94$ and "*b*" value equals to 2.550 (CI ± 0.64) indicate that this relationship is robust, in spite of a narrow range in sizes evaluated. The condition factor ranging from 0.0488 to 0.0498 also did not present significant differences between the sexes ($p = 0.166$). The mean k values per length class followed the biomass gain, regardless of the coefficient *b* estimated, which was lower than 3 (isometry) ($p < 0.05$), indicating that in this phase of relative growth, the species presents a larger increase in length in relation to weight (Fig. 3b).

Relationships between fish size and otolith size were described using a power regression model between measures and were statistically significant ($p < 0.05$). The coefficients of determination showed values ranging from 0.66 to 0.89 (Tab. 1). Otolith length (OL) ranged from 9.65 to 15.25 mm (mean ± SD = 12.60 ± 0.95), height (OH) from 3.65 mm to 5.45 mm (mean ± SD = 4.29 ± 0.31), and weight (OW) from 0.03 g to 0.11 g (mean ± SD = 0.05 ± 0.01) for all samples.

Tab. 1. Power regression relationships between fish size *vs* otolith size and measures of otoliths of *Pomatomus saltatrix*. Number of specimens (*n*) and coefficients of determination (r^2) and parameters of power equations. r^2: Correlation Coefficient; '*a*' and '*b*': regression parameters; CI: 95% confidence interval; OL: otolith length; OH: otolith height; OW: otolith weight; TL: total length; TW: total weight.

Relationship between	*n*	*a*	± CI (*a*)	*b*	± CI (*b*)	r^2
TL *vs* OL	258	1.2294	0.1750	0.5899	0.2860	0.90
TL *vs* OH	288	0.6828	0.2280	0.4667	0.0400	0.65
TL *vs* OW	325	6.49E-05	0.00003	1.6510	0.1158	0.71
TW *vs* OL	258	2.3702	0.2427	0.2370	0.0145	0.80
TW *vs* OH	325	1.3187	0.1596	0.1664	0.0172	0.53
TW *vs* OW	226	0.0004	0.0001	0.6795	0.0440	0.81
OL vs OH	259	3.464	0.3887	0.8880	0.0710	0.67
OL *vs* OW	222	6.17E-05	0.00002	2.5996	0.1174	0.90
OH *vs* OW	281	11.2370	0.8932	0.3088	0.0250	0.68

The shape of the *sagittae* otolith of adults is rectangular to lanceolate with the anterior region rounded-lanceolate and the posterior region oblique or oblique-rounded. The dorsal border is lobed to sinuous and ventral border is sinuous to irregular. The profile is concave and flattened. The *Sulcus acusticus* shows a horizontally oriented medial position with ostial funnel of tubular form moderately curved.The best linear regressions between the sizes of fishes and otoliths were: TL *vs* OL, $r^2 = 0.90$; OL *vs* OW, $r^2 = 0.90$; TW *vs* OW, $r^2 = 0.81$; TW *vs* OL, $r^2 = 0.80$. The relationship OL *vs* OW showed a negative allometric growth (t-test, $p < 0.05$), reinforcing the pattern of a predominant length growth upon weight, resulting in the elongated shape (Fig. 4).

Discussion

Our results showed that the relative growth and the relationships between fish size and otolith size might be used as valuable tools for fisheries management and research. Such applications require the use of morphometric variables from data collected in the field to be transformed into appropriate indices. First, the most commonly used in any analysis of fishery data is the length-weight relationship for estimating the biomass from length. It also provides information on the condition of fish, which is frequently used for comparisons at different scales (Moutopoulos, Stergiou, 2002). Second, the shape and the relationship between the length of a fish and its otolith measures have provided important information to identify species, and to estimate fish length from otoliths. In fact, Aguilera *et al*. (2013) produced length frequency distributions of fishes from otoliths recovered in archaeological sites.

The Comparisons of bluefish LWR in this work and those previously reported in the literature showed variations in the form the species grows (Frota *et al*., 2004; Ak *et al*., 2009; Bok, *et al*., 2011). Such comparisons indicated that the value of the slope *b* varies between 2.509 (negative allometric growth) and 3.330 (positive allometric growth) including the results of this study.

Cumplido *et al*. (2018), working within the same region in the southeastern coast of Brazil, observed *b* values similar to those reported here, despite the fact that their size range included smaller fishes. This negative allometric growth pattern ($b = 2.55$) was slightly smaller than that observed for the southern coast of Brazil ($b = 3.05$, positive allometric growth) (Bernardes, Rossi-Wongtschowski, 2000; Haimovici, Velasco, 2000), slightly higher than the Mediterranean ($b = 2.52$) (Bok *et al*., 2011), and the middle Brazilian coast ($b = 2.50$, negative allometric growth) (Frota *et al*., 2004). These observed differences in the LWR estimated parameters are highly affected by food availability, reproductive periods, migratory activities and abiotic factors (Rossi-Wongtschowski, 1977; King, 1995). Furthermore, sampling associated variables, including sample size and the length range of individuals also influence the LWR parameters.

The variations of the condition factor (k) for the strata of TL evaluated are related to the fluctuations of the sexual cycle, for both genders. Indeed, the higher values of k increased proportionally with size and sexually maturity. Many authors suggest that these variations in k reflect specific environmental conditions such as temperature and salinity of seawater, food availability, and inherent species conditions including the age of the fish, sex, amount of fat reserve, degree of muscular development and changes in maturity stages (Barnham, Baxter, 1998; Froese *et al*., 2006; Muchlisin *et al*., 2017).

In our study, no noticeable intraspecific differences occurred among sexes and otolith pairs for the evaluated length strata of bluefish, which permitted the presentation of the grouped sexes model. Similar findings were obtained by Zengin *et al*. (2017) and Bal *et al*. (2018). Nevertheless, Hare, Cowen (1995) reported that these differences may occur due to the variability in individual growth rates. According to Froese (2006) the sample size, the size range of specimens, differences across populations, gonadal maturity, and preservation techniques could explain intraspecific differences and in the allometric coefficients. This type of relationship between morphometric and morphological characteristics between parts of an organism has been widely applied for several species, such as *Psenopsis cyanea* (Alcock, 1890), *Pterygotrigla hemisticta* (Temminck, Schlegel, 1843), *Bembrops caudimacula* Steindachner, 1876 (Aneesh Kumar, 2017) and *Otolithes ruber* (Bloch, Schneider, 1801)

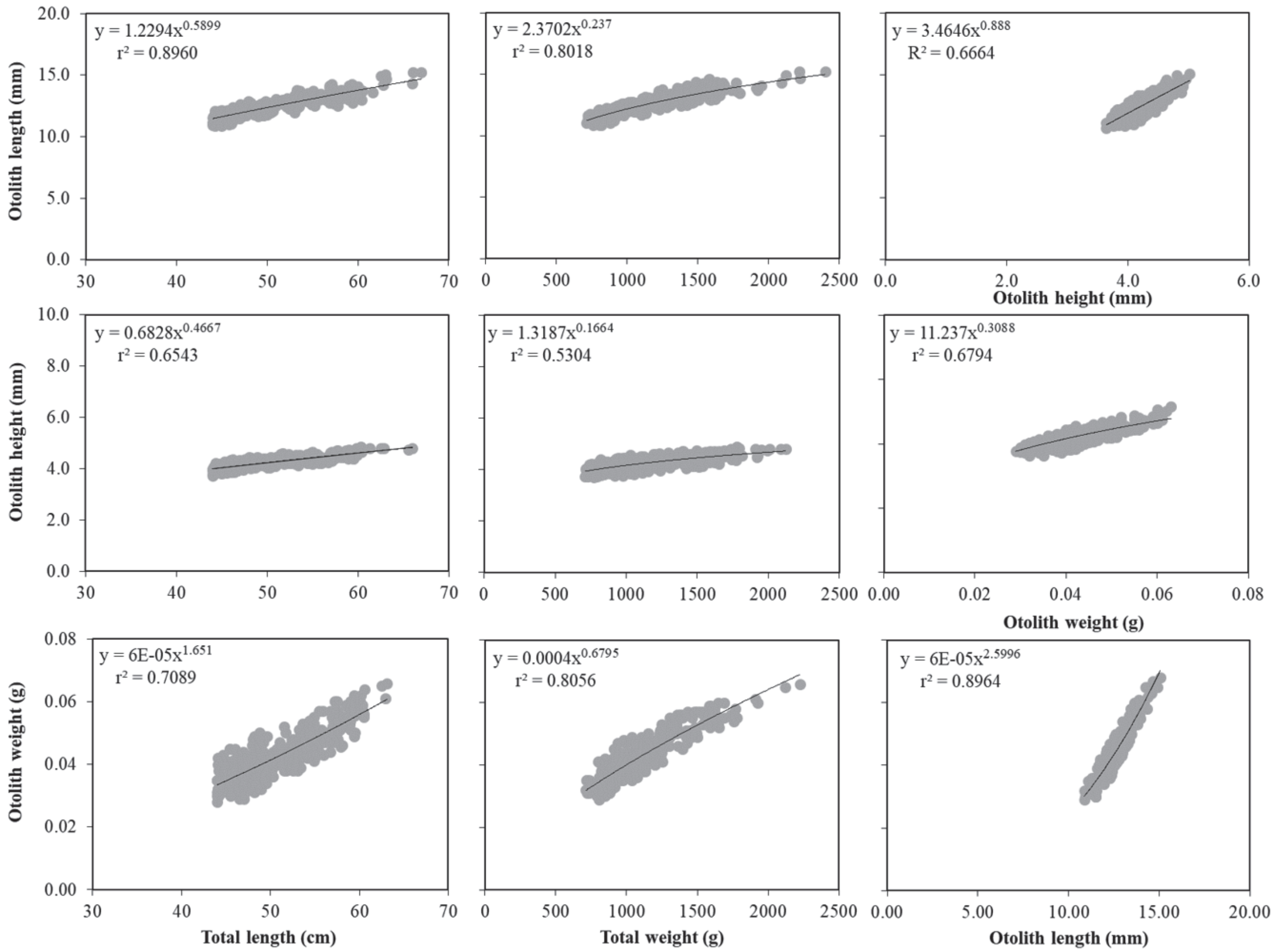

Fig. 4. Relationship between fish size and otolith size and measures of otoliths of *Pomatomus saltatrix* captured off the Brazilian coast in the southeastern Atlantic Ocean.

(Rahnama *et al*., 2017), demonstrating the importance of this tools to evaluate populations or stocks.

Otoliths have long been recognized as one of the most useful fish anatomic structures because of their accretionary growth and species-specific shape, often used to determine the age of fishes. Additionally, otolith microchemistry has been used in recent years to unveil aspects of fish species life cycle (Fraile *et al*., 2016). However, these analyzes are costly and dependent on sensible equipment. Thus, a simplest and most accessible way to obtain information about a population and/or stock is to proceed with otolith length and weight measurements, besides LWR, for comparative studies. Otoliths are also used for identification/discrimination of populations (Stransky *et al*., 2008), ecomorphological studies (Volpedo, Vaz dos Santos, 2015) and the determination of fish prey identity in feeding studies (Tarkan *et al*., 2007). Moreover, in some fish species, age can be determined by otolith weight due to high correlation (Cardinale, Arrhenius, 2004).

Most studies providing relationships between otolith morphology and the total length of bluefish are restricted to the Mediterranean and Black Sea (Ceyhan, Akyol, 2006; Cengiz *et al*., 2012; Zengin *et al*., 2017; Bal *et al*., 2018). Our results for the southwestern Atlantic showed highest correlations between TL *vs* OL (r^2 = 0.89), OL *vs* OW (r^2 = 0.89), TW *vs* OW (r^2 = 0.80) and TW *vs* OL (r^2 = 0.80), indicating that these models may be used as functional tools for estimating fish size from otolith dimensions. Bal *et al*. (2018) observed that the length and height of the otoliths were the best predictors for the TL of bluefish from commercial catches in the Turkish Sea. Other authors registered that otolith length is a good predictor of fish size with regression coefficient higher than our study (r^2 = 0.93 - Ceyhan, Akyol, 2006), lower (r^2 = 0.61 - Zengin *et al*., 2017) and similar (r^2 = 0.88 - Bal *et al*., 2018; r^2 = 0.89 - Cengiz *et al*., 2012). These high r^2 values indicating the good applicability of this tool, *i.e.*, a high level of precision in measurement of the data should imply a high accuracy in coefficient of determination and the possibility to analyze samples with a large number of individuals, reducing bias derived from smaller sample sizes.

The divergence found in the relationship of fish size and otoliths of bluefish obtained in the present study, compared with other studies, is justified by differences in the size range of specimens analyzed. Moreover, data from the literature corresponds to the populations of eastern Atlantic Ocean bluefish, the Mediterranean and the Black Sea. Moreover, all populations presented a positive relationship between total fish length and otolith length, suggesting that this is a strong characteristic of the *sagittae* otoliths of this species, corroborating with our study.

Due to the limited research and data availability on *P. saltatrix* in the southeastern coast of Brazil, comparisons between fish size *vs* otolith size with local previous research were not possible. However, this research is a new contribution in the studies of otolith dimensions as a predictor of size for this fish species. The equations here derived, showing high correlations, may be used as estimators of the selected variables in population dynamic and stock assessment studies of the species. Thus, the morphometric relationships are shown to be useful tools for fisheries management.

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