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Composition and cross-shelf distribution of ichthyoplankton in the Tropical Southwestern Atlantic

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HIGHLIGHTS

- The cross-shelf distribution, abundance, and composition of ichthyoplankton are key ecological features.
- Eggs of family Engraulidae were the most abundant and represented 40.8% of the total eggs.
- The highest abundance was for the anchovy *Anchovia clupeoides*.
- The largest concentration of fish larvae and eggs was found on the outer shelf.
- Results provide a baseline assessment of a poorly studied region of the planet.

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ABSTRACT

The spatial distribution, abundance, and composition of ichthyoplankton are key ecological features for the conservation of biodiversity and sustainability of fisheries. Despite their importance, knowledge about these features in the equatorial waters of the planet is still scarce. The aim of this study was to assess these features in the Tropical Southwestern Atlantic (northeastern Brazil). Two oceanographic cruises were carried out (2010) on the continental shelf. The collections were performed at 54 stations distributed in three coast parallel profiles covering a wide geographical area (20,100 km^2). A total of 3723 fish larvae and 3829 fish eggs were sampled. Larval identification resulted in 15 taxa belonging to 13 families. Eggs of family Engraulidae were the most abundant and represented 40.8% of the total eggs. The largest concentration of fish larvae and eggs was found on the outer shelf, because of the mixture of coastal and oceanic species. On the continental shelf, the abundance of fish larvae was higher near the marine protected area, mesophotic reefs and large tropical mangrove ecosystems. The present results provide a baseline assessment of a poorly studied region of the planet along a coast with high turbidity, and sea surface temperatures. Moreover, the results highlight the need for rigorous monitoring to detect shifts in diversity and abundance of ichthyoplankton on a continental shelf with a large number of rich tropical ecosystems.

1. Introduction

Ichthyoplankton diversity, cross-shelf distribution and abundance are essential diagnostic features for biodiversity conservation, sustainability of fisheries resources, and the goods and services of marine ecosystems (Schuhmann and Mahon, 2015). Ichthyoplankton assemblage diversity results from adult spawning strategies and oceanographic influences (Álvarez et al., 2015; Koched et al., 2015; Sabatés et al., 2007). Along the continental shelf, ichthyoplankton species composition is strongly influenced by proximity of the coast (Franco et al., 2006; Muhling et al., 2008). Closer to the coast, continental runoff also plays an important role in ichthyoplankton species composition (Lopes et al., 2006), mainly owing to the occurrence of mangroves, deltas, and estuaries. Estuarine ecosystems contain natural resources and ecosystem services of immense value to the environment and humanity (Carney et al., 2014; Giri et al., 2015). These include fisheries, carbon storage, and exportation to oceans and nursery habitats of fish larvae (Manez et al., 2014; Sandilyan and Kathiresan, 2015).

Studies on the distribution of ichthyoplankton have been performed mainly in the subtropical and temperate regions of large continental shelf, particularly in the Indo-Pacific, Antarctic,

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North Atlantic Ocean, and Mediterranean Sea (Koubbi et al., 2009; Pattrick and Strydom, 2008; Rodriguez et al., 2009; Somarakis et al., 2011). In the South Atlantic, few studies have analyzed the abundance and diversity of larvae and eggs of fish species (Freitas and Muelbert, 2004; Macedo-Soares et al., 2014). Thus, our current knowledge is focused on subtropical and temperate regions, despite the importance of tropical ecology in the early life history of fishes and its implications for effective management of fisheries resources (Govoni, 2005).

Studies on ichthyoplankton in Tropical southwestern Atlantic (TSA) coast are scarce (Bezerra-Junior et al., 2011) and little is known about their composition and abundance on this important continental shelf. This area can be characterized by a narrow shelf (<40 km) without upwelling and subject to a tropical climate, but with high fish diversity (Freitas and Lotufo, 2015). Therefore, one might hypothesize that on tropical semiarid coasts, fish eggs and larvae might be controlled by the proximity to the coast, tropical reefs and estuaries/mangroves. To overcome this scarcity of information, the objective of this study is provide a baseline assessment of the composition, abundance, and cross-shelf distribution of ichthyoplankton in a tropical continental shelf (TSA, northeastern Brazil). This study aimed to advance the knowledge of fish larvae and eggs and provide new insights for future monitoring and conservation projects related to fisheries resources.

2. Materials and methods

2.1. Study area

The TSA coast (northeastern Brazil) is marked by a strong seasonal rainfall regime, with two well-defined periods (Dias et al., 2013). The climate is tropical semiarid, and it is influenced by oceanic and atmospheric processes that determine the distribution of rainfall (Marengo et al., 2016). A rainy period extends from January to June, and a dry period from July to December. Tides are semidiurnal with a maximum tidal amplitude of about 3.5 m and a minimum of −0.1 m (Rabelo et al., 2015).

The regional climate, including seasonal variation of rainfall, is regulated by the Intertropical Convergence Zone (ITCZ). The magnitude of the ITCZ displacement is affected by El Niño Southern Oscillation (ENSO) and follows the regions where sea surface temperature (SST) is higher (Kayano et al., 2009). "El Niño" causes dry conditions in this region, and "La Niña" produces rainy conditions (Marengo et al., 2016).

The study area (Fig. 1) has a narrow (minimum of 22 km) and shallow (60 m at the shelf break in the study area) shelf with an abrupt transition to steep slopes (∼11°) along the Equatorial Margin (Knoppers et al., 1999). The modern relief of the northeastern Brazilian Continental Shelf is commonly related to high-energy sedimentary and hydrodynamic processes (Gomes et al., 2014).

The study area contains four important features. The first is a Offshore Marine Protected Area (MPA) named "Parque Marinho Pedra da Risca do Meio" (PEMPRM), one of the few fully submerged marine protected areas in the South Atlantic (B13 and C13 in Fig. 1) (Andrade and Soares, 2017), which has tropical sandstone reefs (Soares et al., 2016a). The second feature is the Parnaíba Delta River, which is one of the few open-mouth deltas on the American continent (A1, A2, and A3 in Fig. 1). The Delta is made up of 82 islands and 700 km of navigable water systems—comparable in size to the deltas of the Nile in Africa and the Mekong in Asia (Paula Filho et al., 2015). The third feature is the presence of mesophotic reef ecosystems under tropical marginal conditions (C13, C14, C15, and C16) in the outer shelf (Soares et al., 2016b). The last important physical feature is the Jaguaribe River drainage basin (near A16 and B16 in Fig. 1), which is responsible for the largest fluvial contribution to the semiarid coast of NE Brazil: approximately 50% of the total fluvial outflow to the semi-arid continental shelf (Dias et al., 2013).

2.2. Sampling and data analysis

During 2010, two oceanographic cruises (July and October) were conducted over the continental shelf during the dry season aboard the research vessel "Prof. Martins Filho". The two surveys data were combined into one grid. Horizontal surface hauls were taken at 54 stations using a 50-cm diameter ring net (300-μm mesh) equipped with a flow meter. Samples were taken at three different distances from the coast: inner (3 km, about 5 m depth), middle (10 km, about 30 m depth), and outer shelf (30 km, about 70 m depth) (Fig. 1), covering a geographical area of approximately 20,100 km^2. All samples were immediately fixed with 4% formalin buffered with borax. More information about the stations is in supplementary material 1 (see Appendix A).

At the laboratory, fish eggs and larvae were sorted and counted. The ichthyoplankton concentration was determined and expressed as eggs per 10 m^3 of filtered water ($n/10$ m^3) and larvae per 100 m^3 ($n/100$ m^3) (Omori and Ikeda, 1984). The frequency of occurrence was calculated from the number of samples in which each family was represented as a proportion of the total number of samples. Identifications of fish larvae were based on descriptions in the literature (Fahay, 1983; Richards, 2005).

Hierarchical cluster ordination based on the Bray–Curtis dissimilarity was used to summarize spatial similarities in the distribution of main larval species (R-mode). Considering that the order in which clusters are joined is controlled by the linkage methods, this study used the unweighted pair-group method with arithmetic averaging (UPGMA). The data were transformed using by log $(X + 1)$ to eliminate the effect of dominant species and the number of zeros in the dataset.

Density data were tested for normality using the Shapiro–Wilk test, and for equal variance using the Levene median test. One-way ANOVA analysis was used to compare the density of fish larvae between the three coast parallel profiles (inner, middle, and outer shelf). The level of significance was established at 5%. These statistical analyses were performed with the Primer 6.0 and PAST programs.

3. Results

A total of 3723 fish larvae and 3829 fish eggs were caught during the cruises. Eggs of family Engraulidae were most abundant and represented 40.8% of the total eggs. The outer shelf presented higher abundances of both eggs and larvae than did the inner and middle shelf (Fig. 2).

Larval identification (Fig. 3) resulted in 15 taxa belonging to 13 families (Gobiidae, Carangidae, Lutjanidae, Engraulidae, Haemulidae, Labridae (Scarinae), Ephippidae, Syngnathidae, Clupeidae, Scombridae, Monacanthidae, Belonidae, and Paralichthyidae). The largest concentration of fish larvae was found on the outer shelf (ANOVA, $p = 0.038$) (Table 1).

The fish egg distribution indicates spawning and recruitment activity in the whole study area (Fig. 4(A)), but especially near the Timonha River (A3/A4), the stations on the MPA (C12), and the mouth of the estuary of the Jaguaribe River (B16), as evidenced by the high densities collected there. Fish larval density was higher at the MPA stations (C12 = 10.71 larvae/100 m^3), near the mesophotic reef ecosystems (C14 = 17.62 larvae/100 m^3, and C16 = 18.98 larvae/100 m^3) and Jaguaribe River on the east coast (Fig. 4(B)). Gobiidae larvae were the most frequent (59.3%), considering all sectors of the continental shelf.

The most frequent families of larvae were the Engraulidae (inner, 50%), Lutjanidae (middle, 44%), and Carangidae (outer shelf,

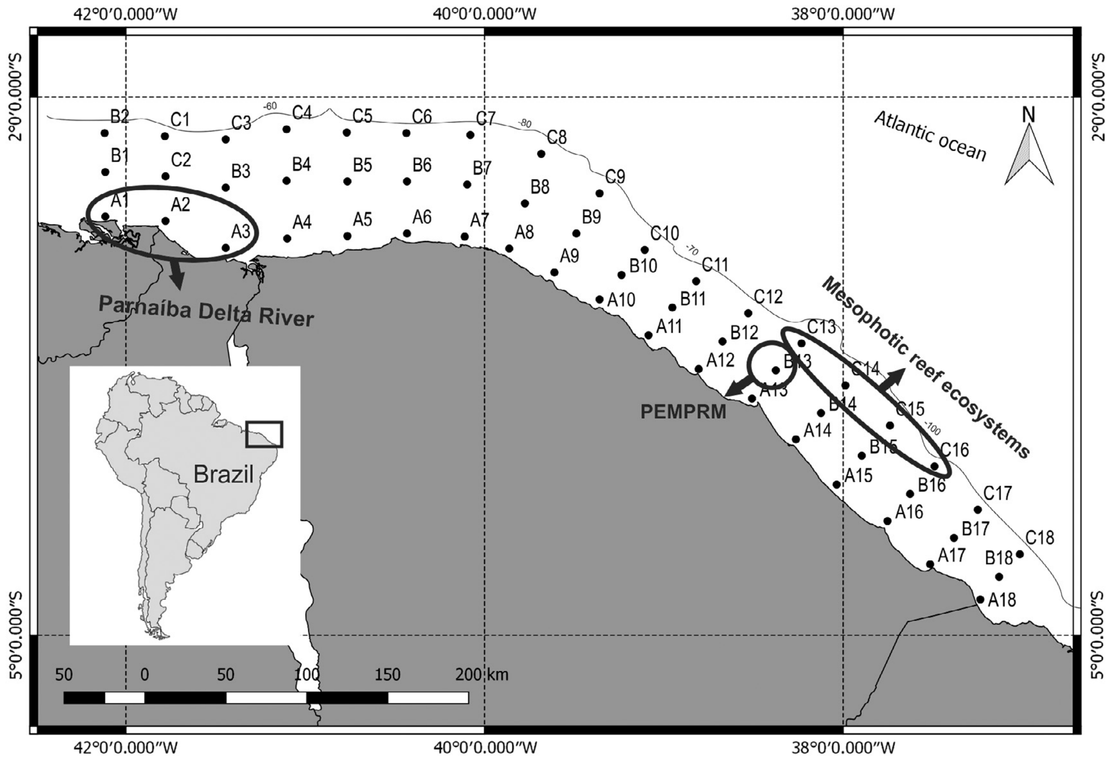

Fig. 1. Distribution of sampling stations along the Tropical Southwestern Atlantic (northeastern Brazil) and the main estuaries. Inner shelf (A), middle shelf (B), and outer shelf (C). The ellipses represent important features such the Parnaíba Delta River, Offshore MPA (*Parque Marinho Pedra da Risca do Meio-PEMPRM*) and mesophotic reef ecosystems.

Table 1
Cross-shelf distribution of larval taxa on the Tropical Southwestern Atlantic Coast. Percent total abundance relative (%). NI: no identification.

Inner shelf			Middle shelf			Outer shelf		
Family	*n*	%	Family	*n*	%	Family	*n*	%
Engraulidae	352	27.5	Gobiidae	287	30.0	Gobiidae	398	27.0
Gobiidae	261	20.4	Engraulidae	130	13.6	Carangidae	324	22.0
Labridae (Scarinae)	242	18.9	Clupeidae	124	13.0	Lutjanidae	180	12.2
Lutjanidae	122	9.5	Lutjanidae	122	12.8	Haemulidae	160	10.9
Clupeidae	120	9.4	Carangidae	121	12.7	Labridae (Scarinae)	143	9.7
Carangidae	84	6.6	Labridae (Scarinae)	108	11.3	Clupeidae	114	7.7
Ephippidae	41	3.2	Ephippidae	27	2.8	Engraulidae	76	5.2
Scombridae	22	1.7	Scombridae	21	2.2	Ephippidae	27	1.8
Haemulidae	12	0.9	NI	13	1.4	Scombridae	31	2.1
NI	10	0.8	Syngnathidae	8	0.8	Syngnathidae	12	0.8
Syngnathidae	8	0.6	Monacanthidae	5	0.5	NI	7	0.5
Paralichthyidae	5	0.4	Haemulidae	3	0.3	–	–	–
Belonidae	3	0.2	–	–	–	–	–	–
Total	1282			969			1472	

56%). Some larvae had low abundance, but were frequently found in many samples, including the Carangidae (42.6%), Lutjanidae (35.2%), and Clupeidae (31.5%). Other families, such as Monacanthidae, Paralichthyidae, and Belonidae, had low frequency (<10%) and low abundance (Table 1).

Fish larvae were sampled in distinct natural habitats, such as estuarine plumes, coastal/shelf, and coral reef habitats. Estuarine fish larvae (Belonidae, Monacanthidae, and Paralichthyidae) occurred only at the inner and middle continental shelf. The coral reef group (Gobiidae, Lutjanidae, Labridae (Scarinae), and Syngnathidae) and coastal/shelf group (Carangidae, Engraulidae, Clupeidae, Ephippidae, and Haemulidae) were common in all samples.

Identification occurred at the species level for 13 of these 15 taxa, and two were identified to the family level. The highest abundance was for the anchovy *Anchovia clupeoides* (Swainson 1839), which was found in 33.3% of all samples.

Cluster analysis evidenced the formation of two groups: the outer stations containing Carangidae sp. 1 and *Anchoa* sp. and the inner portion with Carangidae sp. 2 and Clupeidae sp. We observed the presence of certain species nearest the outer continental shelf regions and another group of coastal species (Fig. 5).

4. Discussion

This study provides new information on the cross-shelf distribution and diversity of ichthyoplankton in the Tropical Southwestern Atlantic. The present results provide a baseline assessment of a poorly understood region of the planet on a coast with high sea surface temperatures in a tropical region. The highest larval densities occurred on the outer shelf, possibly due to the mixture of coastal, reef, and oceanic species. In this region, mesophotic reef ecosystems inhabited by diverse species of fish have been recorded (Soares et al., 2016b). Moreover, the high

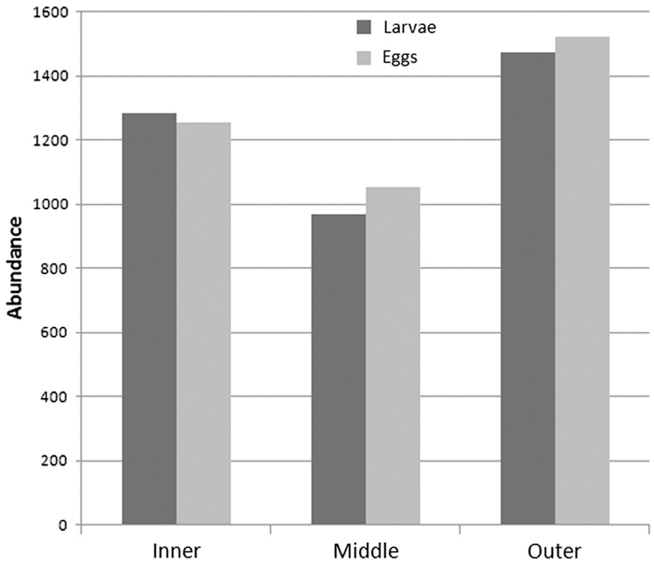

Fig. 2. Number of collected eggs and larvae in each profile on Tropical Southwestern Atlantic coast (northeastern Brazil).

density in the outer shelf may be due to the complex life cycle of fish. For several species, pelagic eggs and larvae are produced in offshore waters (Able et al., 2006).

Results of the distribution of egg and larval assemblages indicated spawning activity of coastal fish species only near the MPA and large tropical estuarine areas, such as the Timonha, Jaguaribe, and Delta do Parnaiba rivers. These coastal regions adjacent to large estuaries and deltas present favorable conditions for the development of resident and migratory fish species that use these areas as nurseries and protection for their eggs and larvae (Coser et al., 2007; Ara et al., 2011). The overlap of fish larvae in the continental shelf, nearshore, and adjacent estuarine habitats is due, in large part, to the common pattern of spawning in the ocean and subsequent transport to estuaries exhibited by many species (Able et al., 2006). In addition, the penetration of estuarine plumes across the continental shelf on ebb tides (Horner-Devine et al., 2015) and advection of coastal waters into fronts on flood tides appear to result in the concentration and dispersion of ichthyoplankton (Hoffmeyer et al., 2009).

In the area with tropical shallow reefs and under the influence of MPA (Freitas and Lotufo, 2015; Soares et al., 2016a), there was a large concentration of fish larvae. The main goal of creating marine protected areas is full protection so that organisms can be restored by the output of eggs and larvae and entry of juveniles and adults into the populations (Kerwath et al., 2013). This region has a fish fauna of about 109 species (Soares et al., 2011). Therefore, the large amount of adult organisms inhabiting the region may explain the observed high abundances. MPAs are frequently expected to fulfill two roles: biodiversity conservation and fishery replenishment—providing recruits to fishing areas outside their borders (Edgar et al., 2014; Leis, 2006).

Most of the families we observed are common in estuarine (Gobiidae), coastal (Engraulidae), and reef ecosystems (Lutjanidae)

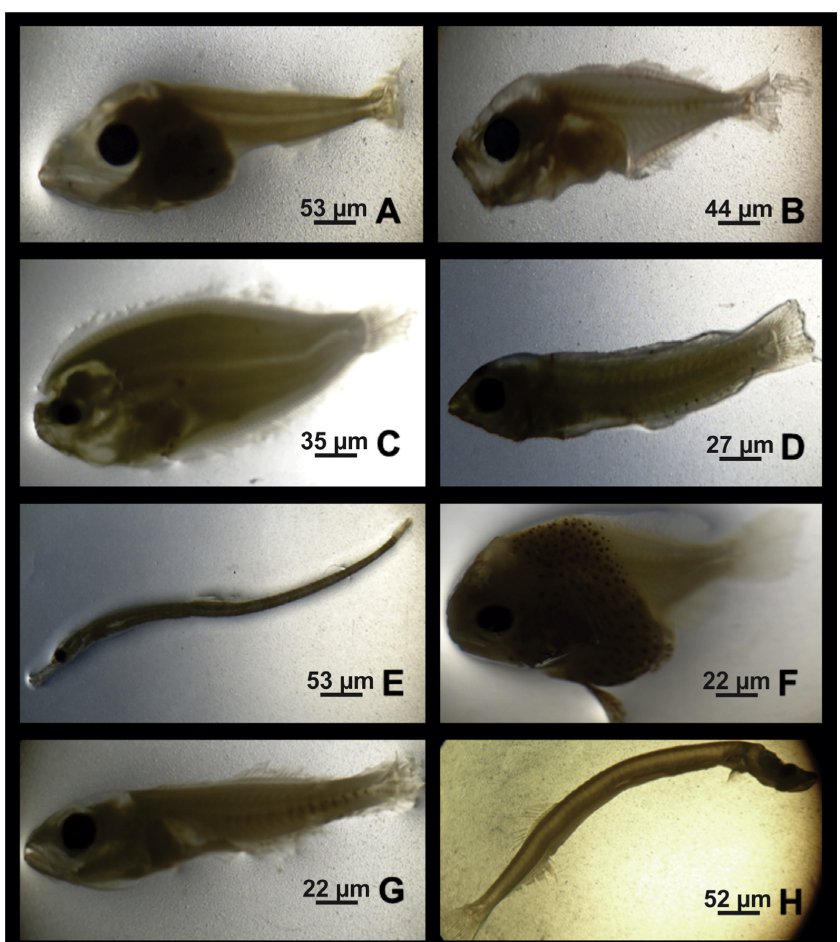

Fig. 3. Illustrated photos of some of the families identified. (A) Scombridae (B) Carangidae (C) Paralichthyidae (D) Labridae (Scarinae) (E) Syngnathidae (F) Ephippidae (G) Labridae (Scarinae) (H) Engraulidae.

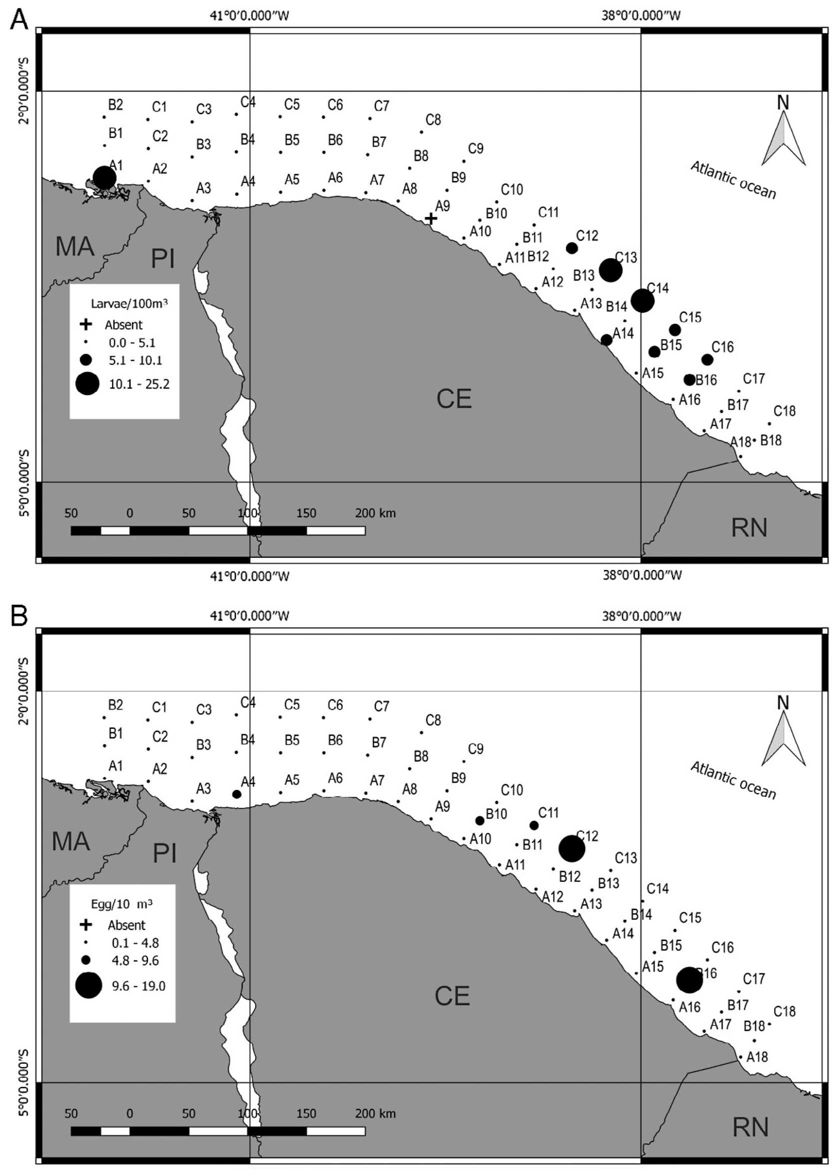

Fig. 4. Total egg density (egg/10 m^3) (A) and total larval density (larvae/100 m^3) (B) in the Tropical Southwestern Atlantic (NE, Brazil) at the inner, middle, and outer profiles. Legend: MA = Maranhão State, PI = Piauí State; CE = Ceará State; RN = Rio Grande do Norte State.

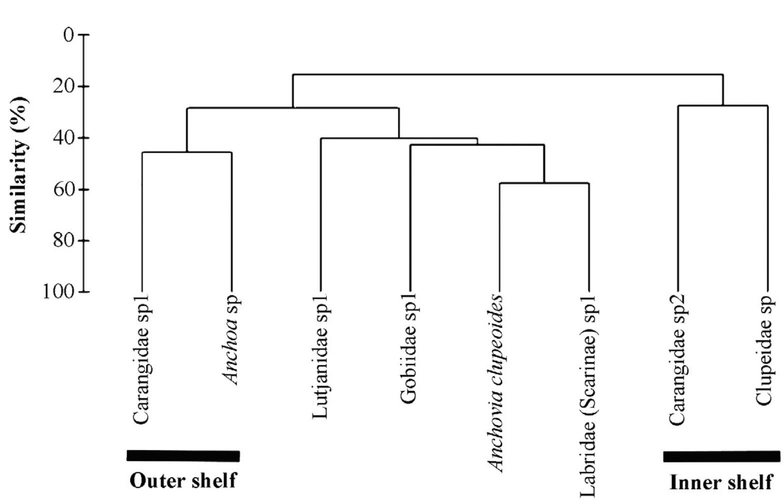

Fig. 5. Hierarchical clustering analyses based on Bray–Curtis similarity showing species/station clusters (R-mode) with relative abundances of cross-shelf distribution of larvae taxa in the Tropical Southwestern Atlantic.

(Richards, 2005). The variety of environments colonized or inhabited by species is related to their survival and reproduction habits (Kerr et al., 2010). In addition, variety in larval composition is a result of oceanographic influences and different kinds of environments in local collections (reef, estuarine, coastal, and oceanic areas) (Floeter and Gasparini, 2000).

Engraulidae were dominant in the distinct sectors of the continental shelf (inner, middle, and outer). These larvae are common in southwestern Atlantic waters (Bezerra-Junior et al., 2011). Adult forms are easily found on the tropical coast of Brazil (Gurgel et al., 2012) and belong to a larger group of important families in the coastal ecosystems of the world (Silva and Araújo, 2000). These organisms exhibit a pelagic habit and use this region for feeding, spawning, and protection (Bloom and Lovejoy, 2012; Coto et al., 1988). Only eggs of family Engraulidae were identified due to the degree of difficulty of this process (Costa and Souza-Conceição, 2009).

Larvae of Clupeidae, Gobiidae, and Carangidae were also very abundant, as such organisms are common in tropical zones with warmer waters (Daly et al., 2013; Arkhipov et al., 2015). Larvae of *Anchovia clupeoides* showed the greatest abundance. These organisms have pelagic habits. They are shoal formers with ellipsoid eggs and spawn on the continental shelf near coastal regions (Fahay, 1983).

The clupeids are organisms of great ecological and economic importance in marine environments and exhibit high fertility. Interestingly, usually the larvae inhabit different regions than the adult organisms (Ara et al., 2011; Oliveira and Fávaro, 2010). The gobies constitute a large proportion of the fishes in both tropical and temperate near-shore marine and estuarine environments, including important representation on tropical reefs (Thacker and Roje, 2011).

Another group with high abundance along the equatorial coast was fish larvae of the family Lutjanidae. Most coral reef organisms have complex life histories, whereby relatively sedentary adults produce pelagic eggs or larvae. Many shallow water snapper species such as lutjanids as well as other ecologically and economically important fishes and invertebrates (groupers and spiny lobsters) use nearshore and reef ecosystems as settlement and juvenile habitats before moving to reefs as adults (D'Alessandro et al., 2011).

Overall, the continental shelf presented a low diversity of ichthyoplankton. This data is contradictory to other studies on tropical continental shelves (Arkhipov et al., 2015; León-Chávez et al., 2010; Li et al., 2014). However, those surveys were conducted on broad continental shelves with strong continental drainage. In the study area, the estuaries only release a significant flow capable of influencing the platform during the rainy season, and are restricted to a few major areas (Dias et al., 2013; Lacerda et al., 2012). Moreover, this survey were conducted in dry season. The rainy season corresponds to the peak in terms of diversity and abundance in other tropical regions like Western Indian Ocean (Jaonalison et al., 2016). This study was conducted along a tropical semiarid coast drained by estuaries with low annual river flow (Dias et al., 2013) with oligotrophic waters, a narrow continental shelf, and regulated by the presence of trade winds that prevent the occurrence of coastal upwellings. The continental shelf in the northeastern Brazil is a typical tropical marine ecosystem and exhibits low primary and fish production; the phytoplanktonic biomass is dominated by pico and nanoplankton, and microbial process prevail (Knoppers et al., 1999; Santos et al., 2016).

Where the shelf is relatively narrow, coastal currents influence the coastline and are associated with relatively low tidal current influence. Two sectors are clearly identified in the tropical semiarid shelf: sediments down to the 20 m isobath that are mostly quartz sand followed by calcareous algae to 70 m depth (Summerhayes et al., 1975). The interaction between these sediment types and the predominant climate suggest a small continental contribution owing to the semiarid climate and the small fluvial flow (Knoppers et al., 1999; Dias et al., 2013), with strong influence on the biota inhabiting coastal areas. The influence of the semiarid climate and the low fluvial input into the ocean need to be studied further to understand these effects on the composition and cross-shelf distribution of ichthyoplankton along tropical coasts.

5. Conclusions

In conclusion, the semiarid continental shelf of the Tropical Southwestern Atlantic is used as a breeding and spawning area for tropical fishes. The largest concentration of fish larvae and eggs was found on the outer shelf, probably because of the mixture of coastal and oceanic species. Moreover, the results support the hypothesis that in the region (during the dry season), the cross-shelf distribution of ichthyoplankton is influenced by the proximity of large tropical deltas/estuaries, mesophotic ecosystems and the offshore MPA. Further studies should be performed to assess seasonal variations and the role of rainfall in the control of fish larvae and egg abundance along tropical semiarid coasts.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.rsma.2017.05.001.

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