

Relationship between abundance of small pelagic fishes and environmental factors in the Colombian Caribbean Sea: an analysis based on hydroacoustic information

Jorge Paramo ^{a,*}, Renato A. Quiñones ^b, Argiro Ramirez ^{b,c}, Rodrigo Wiff ^b

^a Instituto de Investigación Pesquera (Inpesca), Av. Cristóbal Colón 2780, Casilla 350, Talcahuano, Chile

^b Departamento de Oceanografía, Universidad de Concepción, Casilla 160-C, Concepción, Chile

^c Instituto Nacional de Pesca y Acuicultura, Apartado Aéreo 10140, Buenaventura, Colombia

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Abstract

The most important pelagic artisanal fishery of the Colombian Caribbean Sea is the Atlantic thread herring (*Opisthonema oglinum*) and the associated species scaled herring (*Harengula jaguana*), round sardinella (*Sardinella aurita*), and scad (*Decapterus punctatus*). The largest aggregations of these small pelagics were found in the La Guajira area, where the local oceanography is modulated by seasonal upwelling intensity. We analysed the associations between the distribution of these small pelagic fishes and the environmental variables. A cumulative frequency method and a Monte Carlo randomization were used to detect associations between fish density and environmental variables. The adults of Atlantic thread herring were found in the upwelling area of La Guajira Peninsula and were associated to waters with temperature and salinity values higher than 25.5 and 36.7 °C, respectively. During December, a nursery area was found in the southern portion of the study area and the juveniles of Atlantic thread herring showed preference for temperatures higher than 27.4 °C. Scaled herring was found to be associated with temperatures (>25.7 °C) and salinities (>36.8). Scad and round sardinella were also associated to temperatures and salinities higher than 25 and 36.6 °C. Our results suggest that the dynamics of the upwelling area may influence the spatial distribution and abundance of small pelagics in the Colombian Caribbean Sea.

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1. Introduction

The most important pelagic artisanal fishery of the Colombian Caribbean Sea is the Atlantic thread herring (*Opisthonema oglinum*) and the associated species scaled herring (*Harengula jaguana*), round sardinella (*Sardinella aurita*), and scad (*Decapterus punctatus*). These fisheries are mainly located off the La Guajira Peninsula, Ciénaga Grande de Santa Marta, and the Magdalena River Delta. Only few surveys have been carried out on these small pelagic fishes in order to assess the abundance and spatial distribution using hydroacoustic methods. The first one was conducted in 1985 (Blanco, 1986), and the other in 1988 was conducted by the Institute of Marine Research (Norway) using acoustic echolocation (Anon., 1989). Major concentrations of pelagic

fishes were found in the Riohacha area for the 1985 survey and in the northern La Guajira Peninsula for the 1988 survey (Fig. 1). Another two surveys were carried out by the Fishing Program of the Instituto Nacional de Pesca y Acuicultura (INPA-VECEP/UE) in 1997 using acoustic-geostatistical methods leading to a biomass estimation and spatial distribution updates for the small pelagic fishes (Paramo and Roa, 2003). These last few surveys found that the patches of small pelagic fishes were distributed mainly in southern La Guajira Peninsula (Paramo and Roa, 2003; Paramo and Viaña, 2003). All studies conducted coincide with the fact that the largest aggregations of small pelagics are found in the La Guajira area.

In the northern Colombian Caribbean, the continental shelf is very narrow, with the 200 m isobath at a distance of only 10 nautical miles (nmi) from the coast. To the west, the shelf widens to a maximum of 25 nmi off Riohacha and then

* Corresponding author.

E-mail address: jparamo@inpesca.cl (J. Paramo).

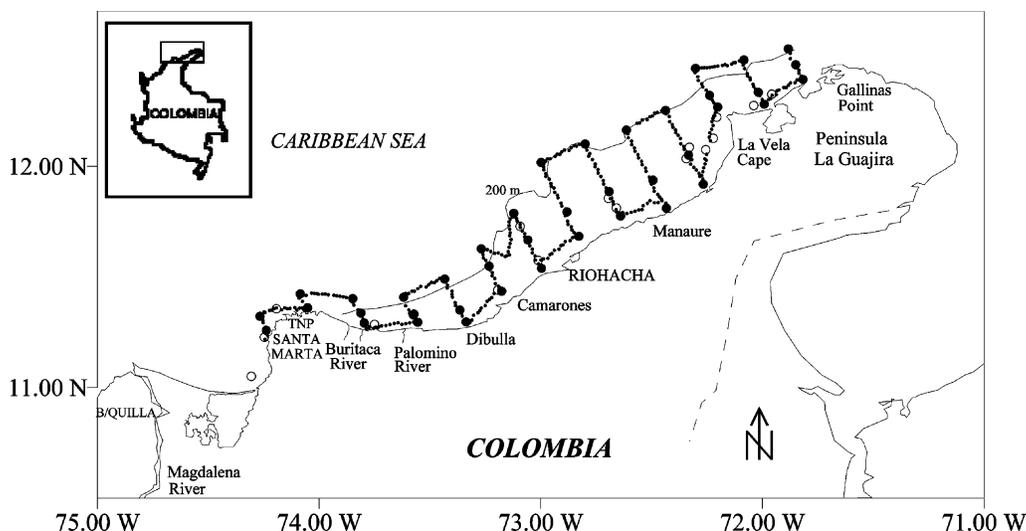


Fig. 1. Acoustic track performed on the Colombian Caribbean during the research surveys. Small circles: elementary distance sampling units; large empty circles: directed fishing trawls; large grey circles: oceanographic stations.

narrows again and almost disappears off the Tayrona National Park (TNP) (Fig. 1). The Colombian Caribbean is under the influence of the north–south displacement of the Inter Tropical Convergence Zone (ITCZ). When the ITCZ is towards the south (dry season), the high-pressure system forces strong and constant westward trade winds. During the same period, the Caribbean current is displaced towards the west. When this current is near the Panama coast, it is deflected southward and then eastward. In this way, the counter-current is formed. When the ITCZ is towards the north (rain season), the trade winds relax and their direction becomes variable due to the low-pressure system. This condition promotes the extension of the counter-current in the northwest axis. In this way, the counter-current forcing is seasonally dependent (Pujos et al., 1986); during the dry seasons (major summer: August–September; minor summer: December–January), the northern zone is affected by the Caribbean current and the upwelling of deep waters. The upwelling magnitude is stronger at La Guajira Peninsula, whose effects reach the waters near the TNP (Blanco, 1986). During the rainy seasons (major winter: September–November; minor winter: May–June), the counter-current reaches even La Vela Cape in La Guajira Peninsula (Bula-Meyer, 1990). However, Blanco (1986) considered that this counter-current would not cross Boca de Ceniza (Magdalena river's mouth). On the other hand, Pujos et al. (1986) mentioned that during dry seasons, this counter-current reaches the Magdalena River's mouth, until it reaches a maximum off the Guajira coast during the most rainy period of the year (October–November).

The major aggregations of these small pelagic fishes found in the La Guajira area, where the local oceanography is modulated by the seasonal upwelling intensity, suggest that environmental conditions were important determinants of their spatial distribution and abundance. Here, we analysed the associations between the distribution of the small pelagic

Atlantic thread herring, scaled herring, round sardinella and scad with environmental variables (temperature, salinity, and oxygen) in the northern part of the Colombian Caribbean Sea. We used data from the two surveys carried out by the INPA-VECEP/UE Fishing Program during 1997.

2. Materials and methods

2.1. Survey designs and equipment

Two hydroacoustic surveys were carried out during July/August and December 1997 between Gallinas Point ($12^{\circ} 24' N-71^{\circ} 48.69' W$) and Santa Marta ($11^{\circ} 16' N-74^{\circ} 14' W$), of the northern area of the Colombian Caribbean Sea. Both surveys had a similar systematic sampling design with 14 parallel transects located perpendicular to the coast covering the entire continental shelf. The inter-transect distance was 12 nmi and elementary distance sampling unit (EDSU) was 1 nmi (Fig. 1).

Nine transects were carried out from 1 to 25 nmi offshore in the areas where the shelf was wider. Five transects were carried out from 1 to 15 nmi offshore in the zone between Dibulla and Santa Marta. On the 25 nmi transects the oceanographic sampling stations were positioned at 1, 15, and 25 nmi from the coast, while on the 15 nmi transects, the stations were located at 1, 5, and 15 nmi from the coast (Fig. 1). Temperature, salinity, and oxygen concentration were measured at a depth of 5 m with a CTDO (Sea Bird Electronics). During the July/August survey, no oxygen data were available because the CTDO sensor was not working appropriately.

The acoustic data were collected using a SIMRAD EK500 echo-sounder and echo-integrator at a frequency of 38 kHz. An equipment calibration was conducted according to SIMRAD specifications (SIMRAD, 1993) before the start of each

survey. Midwater trawls were used to identify echo-traces and to determine the species size-frequency distribution (MacLennan and Simmonds, 1992). The target strength (TS) was assumed from the equation suggested by Foote (1987) for physostome fishes:

$$TS = 20 \log \bar{L} - 71.9 \text{ (dB)} \quad (1)$$

where \bar{L} is the average length (cm) of the fish sample obtained by fishing trawls.

The nautical area scattering coefficient (S_A) measured in $m^2 \text{ nmi}^{-2}$ was converted to fish density ($t \text{ nmi}^{-2}$) using this TS and values of echo-integration for each EDSU.

2.2. Habitat–fish density relationships

A cumulative frequency method and a Monte Carlo randomization (D’Amours, 1993; Perry and Smith, 1994) were used to detect associations between fish density and environmental variables (i.e. temperature, salinity, and oxygen). First, the relative cumulative frequency distribution (CFD) was calculated for each of the environmental variables. Subsequently, we weighted the CFD for each environmental variable by fish density. The comparison of the unweighted CFD of the environmental variable with the weighted CFD of the environmental variable provides evidence as to whether the population is associated with the environmental variable or not. If the population is randomly distributed in relation to the environmental variable, the two curves will accrue similarly and the two curves will not be significantly different. In contrast, if the population is associated with a particular environmental variable, the slope of the weighted CFD should be steeper than that of the unweighted environmental variable. The opposite is valid in the case of no association between a particular range of the environmental variable and fish density. The CFDs for the environmental variables (i.e. temperature, salinity, and oxygen) were calculated as follows:

$$f(t) = \frac{1}{n} \sum_{i=1}^n I(x_i) \quad (2)$$

with the indicator function

$$I(x_i) = \begin{cases} 1, & \text{if } x_i \leq t, \\ 0, & \text{otherwise} \end{cases}$$

where t represents an index ranging from the lowest to the highest value of the habitat variable at a step size appropriate for the desired resolution.

In order to relate the environmental variables with the fish density, only the EDSUs within a 2 nmi radius from each oceanographic station were used. Then, we used the CFD of the environmental variable multiplied by fish density:

$$g(t) = \frac{1}{n} \sum_{i=1}^n \frac{y_i}{\bar{y}} I(x_i) \quad (3)$$

where y_i is a specific fish density variable in the set i within the t range of the environmental variable and \bar{y} is the mean fish density.

In order to determine the statistical significance (P) of the difference between the curves, the maximum absolute vertical distance between $g(t)$ and $f(t)$ was calculated as:

$$\max_{\forall t} |g(t) - f(t)| = \max_{\forall t} \left| \frac{1}{n} \sum_{i=1}^n \left(\frac{y_i - \bar{y}}{\bar{y}} \right) I(x_i) \right| \quad (4)$$

and its probability under the hypothesis of a random relation between both CFDs was evaluated by producing a Monte Carlo frequency distribution for the statistic in Eq. (4). Thus, after determining the maximum absolute difference between the two curves (s), we compare it with the distribution of the maximum absolute differences from 2000 randomizations of the Monte Carlo resampling for fish density and the environmental variable.

3. Results

During both the July/August (Fig. 2a) and December (Fig. 2b) surveys, sea surface temperature (SST) increased in a southwesterly direction from the area of the main source of upwelling (north of La Vela Cape). This tendency was more pronounced during the second survey. During the first survey, warm water was retained close inshore between Manaure and the Palomino River, and the thermal gradient diminished with increasing distance offshore. During the second survey, a similar pattern was seen in the area between Camarones and Dibulla.

Results of the statistical analysis show that during the July/August survey, all small pelagics, except the scaled herring, were primarily associated with the sea surface temperature (SST) ($P < 0.01$ and $P < 0.05$). The only species that showed a significant association ($P < 0.05$) with salinity were the adults of the Atlantic thread herring and the round sardinella (Table 1, Fig. 3). It should be noted that in this analysis the adults and the juveniles of the Atlantic thread herring were separated. This was possible since the identification fishing hauls and the echo-integration records showed a more coastal spatial distribution for the juveniles than the adults. Off Camarones, the adults were found approximately 17 nmi offshore and between Santa Marta and Dibulla they were closer inshore. The Atlantic thread herring adults were associated with temperature ($P < 0.01$) and salinity ($P < 0.05$), while the juveniles were only associated with temperature ($P < 0.01$). The scaled herring showed no significant association with either of the two oceanographic variables. The round sardinella showed consistent association with temperature ($P < 0.01$) and salinity ($P < 0.05$), while the scad was only associated with temperature ($P < 0.05$). Atlantic thread herring were associated with warmer temperatures while round sardinella and scad with cooler temperatures. The patterns of salinity associations

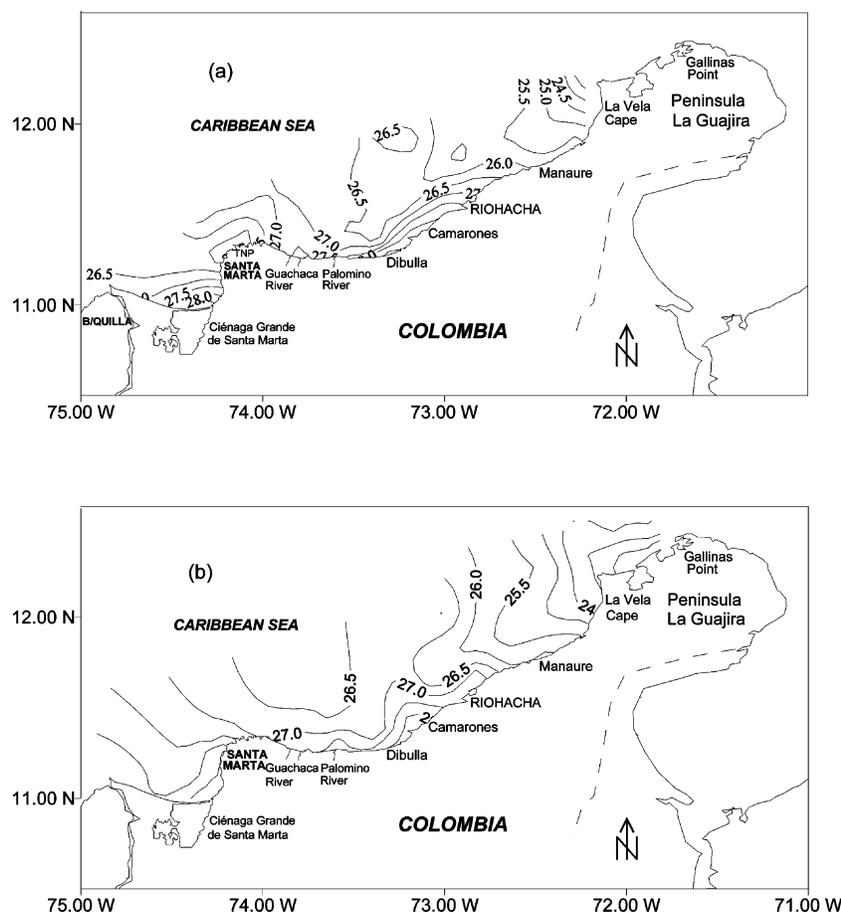


Fig. 2. SST: (a) during the July/August survey; (b) during the December survey.

showed that the Atlantic thread herring adults were associated with lower salinities and round sardinella with higher salinities (Fig. 3).

Results of the randomization test of association between fish density with environmental variables (temperature, salinity, and oxygen) during the December survey (Table 1),

show significant associations mainly with temperature and salinity for most species. When the analysis was carried out using the data of the entire study area, a significant association was found for the Atlantic thread herring with salinity and oxygen, but not with temperature. However, Paramo and Roa (2003) found two spatially separated aggregations of the

Table 1

Results of the univariate randomization test of association between fish density and surface temperature, salinity and oxygen during the July/August and December 1997 surveys. The number below each *P*-value is the preference range for the environmental variable

Fish species	July/August, 1997		December, 1997		
	Temperature (°C)	Salinity (psu)	Temperature (°C)	Salinity (psu)	Oxygen (ml l ⁻¹)
Atlantic thread herring, all areas	0.00 * (26.68–27.48)	0.04 ** (36.50)	0.07	0.05 ** (36.71–36.76)	0.00 * (3.09–3.14)
Atlantic thread herring adults	0.00 * (26.76–27.46)	0.04 ** (36.50)	0.00 * (24.44–24.54)	0.001 * (36.81–36.84)	0.17
Atlantic thread herring juveniles	0.002 * (26.70–27.50)	0.78	0.01 ** (27.37–27.47)	0.51	0.24
Scaled herring	0.11	0.23	0.00 * (25.78)	0.00 * (36.81–36.82)	0.01 * (3.20)
Round sardinella	0.001 * (25.75–25.85)	0.03 ** (36.72–36.73)	0.001 * (25.64–25.84)	0.00 * (36.68–36.70)	0.04 ** (2.54–2.63)
Scad	0.04 ** (25.58)	0.07	0.003 * (25.74–25.84)	0.00 * (36.68–36.69)	0.17

* $P \leq 0.01$.

** $0.01 < P \leq 0.05$.

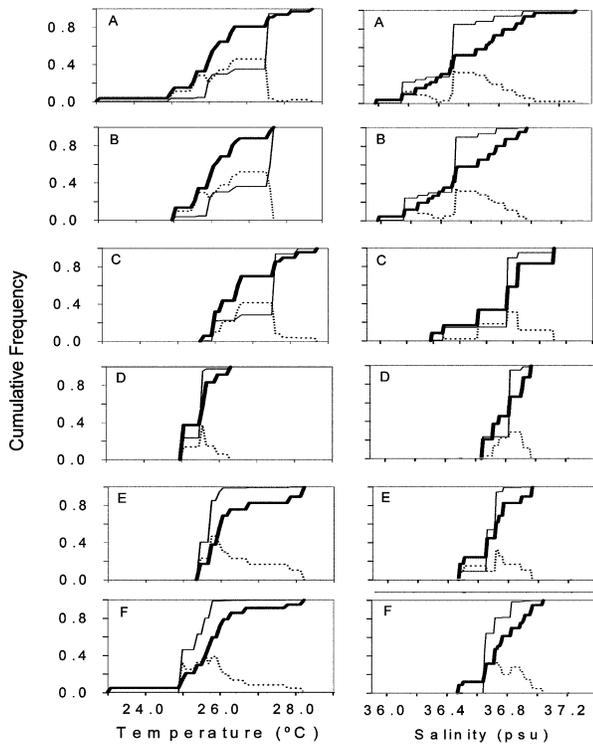


Fig. 3. CFD of the habitat variables, temperature (left) and salinity (right) during the July/August 1997 survey; $f(t)$: thick line; $g(t)$ where t is an index: thin line; absolute difference between $g(t)$ and $f(t)$: dotted line. (A) Atlantic thread herring all area; (B) Atlantic thread herring adult; (C) Atlantic thread herring juvenile; (D) scaled herring; (E) round sardinella; (F) scad.

Atlantic thread herring in December 1997, the larger one was at the base of La Guajira Peninsula and the smaller one was in the south, between Buritaca River and Camarones (Fig. 1). These two patches seemed to reflect population structure, since individuals from the south were much smaller (averaging 12.1 cm total length) than individuals from the north (27.1 cm average total length). In this sense, we also examined these two populations separately, the northern aggregation (adults) showed significant association with temperature and salinity ($P < 0.01$), while the southern aggregation (juvenile) was only associated with temperature ($P < 0.05$). The adults and juveniles of the Atlantic thread herring showed different association ranges with temperature. The Atlantic thread herring adults were associated with cooler temperatures whereas the juvenile with warmer temperatures. Scaled herring, round sardinella and scad were associated with similar temperatures (Table 1, Fig. 4). Scaled herring showed a strong significant relationship ($P < 0.01$) with all three environmental variables under study. Similarly, sardinella showed significant relationships with temperature, salinity ($P < 0.01$), and oxygen ($P < 0.05$). However, round sardinella preferred conditions of lower salinity and oxygen than the scaled herring. The scad showed a strong significant relationship with temperature and salinity ($P < 0.01$), but not with oxygen (see Fig. 4). Only two of the four species, scaled herring and round sardinella, showed significant relation-

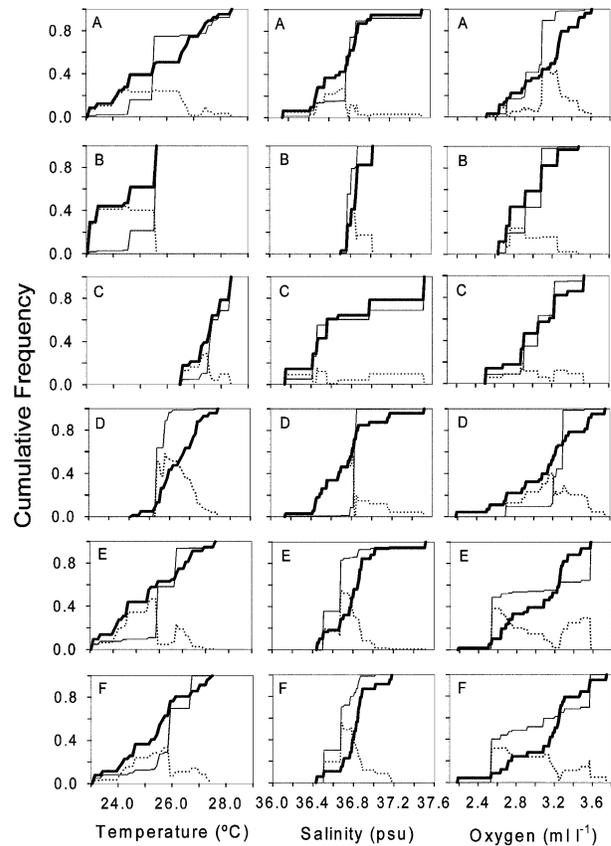


Fig. 4. CFD of the habitat variables, temperature, salinity, and oxygen (from left to right) during the December 1997 survey; $f(t)$: thick line; $g(t)$: thin line; absolute difference between $g(t)$ and $f(t)$: dotted line. (A) Atlantic thread herring all area; (B) Atlantic thread herring adult; (C) Atlantic thread herring juvenile; (D) scaled herring; (E) round sardinella; (F) scad.

ships with oxygen ($P < 0.05$), the latter tolerating conditions of lower oxygen.

4. Discussion

The main upwelling coastal ecosystems in temperate zones are characterized by strong seasonal or permanent equatorial winds, a vertical current structure, and a persistent wind-induced offshore drift of surface waters (Brink, 1983). These ecosystems present high rates of primary productivity (Roy, 1998; Mackenzie, 2000), and they usually support large populations of pelagic fish (Pauly and Tsukuyama, 1987; Cury and Roy, 1989). In tropical environments, such as the Colombian Caribbean Sea, these conditions are quite different. Generally, two monsoon or trade wind seasons replace the four seasons of temperate zones, differentiated by wind patterns, rainfall, and currents. In addition, the concentration of dissolved nutrients is lower, except in upwelling areas (Johanes, 1978).

Our results suggest that the dynamics of the seasonal upwelling in the northern zone of the Caribbean Colombian Sea is a significant factor in modulating the spatial distribution of the small pelagic species. In the December 1997

survey (i.e. the period of greater influence of seasonal upwelling), the Atlantic thread herring is normally found in this region, although it avoids the centre of the upwelling. This species has a seasonal migratory behaviour towards the open sea during periods of increased wind strength or when upwelling intensifies. These conditions produce an increase in the turbulence of coastal areas, forcing the Atlantic thread herring to move towards clearer waters offshore (Valdes and Sotolongo, 1983). In the northern area, the adults of the Atlantic thread herring prefer lower temperatures and higher salinity, while the juvenile aggregations are found further south. This could be of importance because the growth rate of the individuals is affected by temperature. As shown by Heath (1992), clupeid juveniles with adequate food supply and within a favourable temperature range will increase their growth rate by approximately 10% for every 1 °C. Accordingly, a nursery area with higher temperatures should promote a faster development of the swimming and feeding capacity and thus a drop of the natural mortality. *Sardinella* was strongly associated with temperature in both surveys (25.64–25.85 °C), which would indicate a preference for relatively cold waters (Johnson and Vaught, 1986; Anon., 1989; Cervigón, 1991). It is also extremely stenohaline and is never found in waters with salinities below 35 (Longhurst and Pauly, 1987). This is in line with our results, since in both surveys, round sardinella was found in areas having salinities of 36.7 for the region off Riohacha. At the same time, environmental preference ranges of scad were similar to those of round *Sardinella*.

All studied species showed strong associations with lower temperatures. This is typical for areas influenced by the seasonal upwelling, which at this time of year (mid-December–April) is at the maximum due to the presence of stronger trade winds. The main centre of the upwelling is in the area between Gallinas Point and La Vela Cape. The exception being the juvenile aggregation of the Atlantic threads herring which preferred higher temperatures in the December survey. For salinity, all species showed strong association patterns preferring higher salinities at the upwelling influenced area. Once again, the exception being the Atlantic threads herring juveniles that showed no significant relationship with salinity. During the December survey, the region between Camarones and the Tayrona National Park was characterized by an increase in surface temperature in an inshore direction. It is important to note that in this region an aggregation of Atlantic thread herring juveniles was found that had not reached mature size ($L_{50\%} = 22.8$ cm) (Finucane and Vaught, 1986), but that they were about to reach recruitment length ($L_r = 15.9$ cm) (www.Fishbase.org). This leads to the hypothesis that the region between Camarones and the Tayrona National Park may be an important retention and nursery area for the Atlantic thread herring. Manjarrés et al. (1998) found that the largest concentrations of zooplankton were found in the area between Gallinas Point and Riohacha. This is in agreement with our results that show that the region influenced by the

upwelling off La Guajira Peninsula may be an appropriate habitat for communities of small pelagic due to the increase in productivity and the quantity of available food for these species.

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