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Horizontal distribution of dominant pelagic fish eggs in West African waters

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Abstract

Early life stages of dominant West African pelagic fishes, most of which are commercially important, are rarely studied especially in Senegalese and Mauritanian coastal waters. The aim of the present study was to examine the horizontal distribution of pelagic fish eggs of European sardine (Sardina pilchardus), anchovy (Engraulis encrasicolus), round sardinella (Sardinella aurita) and horse mackerel (Trachurus trachurus) in winter-spring and summer. The two seasons revealed two contrasting environmental conditions. While in late winter strong upwelling shaped the environmental conditions, in summer a warm tropical influx of surface water from Senegal towards Mauritania was observed. Fish eggs occurred in both seasons along the shelf coasts of Mauritania and Senegal. The distribution of fish eggs was related to temperature, salinity and chlorophyll data obtained at each sampling position. Eggs of most species were concentrated in coastal waters off the Banc d'Arguin, in Saint-Louis and along the Senegalese sub-region. Spawning occurs mainly during winter and would be linked to environmental changes in particular temperature that significantly vary eggs distribution as notified with Sardina pilchardus and Sardinella aurita during late winter. Moreover, results have shown a significant role of other habitat factors such as chlorophyll, depth and also the continental shelf-break, as a mechanism of retention of fish eggs.

Keywords: fish egg abundance, early stages, ichthyoplankton, upwelling, Canary Current Large Marine Ecosystem, Senegal, Mauritania.

1. Introduction

Small pelagic fishes constitute a major fisheries resource along the coast of Western Africa. This area is very productive because of the upwelling of cold and nutrient rich sub-surface water during the upwelling season along the coast. Fisheries have an important social and economic role in the Western Africa, contributing to food, employment and income, with a high dependency on fish as protein source for human nutrition. The fishery sector contributes on average to more than 4.3 percent of the gross domestic product of these countries [1]. In upwelling ecosystems, small pelagic fishes typically constitute the bulk of landings, with annual catches ranging in 2014 from 2 to around 2.5 million tons in West Africa [2].

Annual catches of some pelagic species severely fluctuated. For instance, landings of the round sardinella (*Sardinella aurita*) started to decline from 2004 after some years of high catches [3] and the fishery started to target other small pelagic species such as horse mackerel and sardine that is now showing signs of overexploitation [4]. A number of management measures exist at national level, for instance in Senegal, such as minimum sizes, closed areas and gear restrictions. On a regional level the RFMO body SRFC (Sub-Regional Fisheries Commission) developed a strategic plan to improve resource use and assessments, of which improving knowledge on areas and habitats of ecological interest is one of the key issues [5]. Hence, the understanding of the role of the ecosystem on fisheries relevant species is the key to improve management options in Western Africa.

In Senegal and the sub-region (Senegal's neighboring countries), relatively few studies have focused on early life-history stages of fishes, in particular fish eggs. The distribution of fish eggs reveals spawning habitats of fishes. Thus, the knowledge of the main spawning habitats may help to define no-take areas for fisheries targeting the species during the spawning period. This may help to increase the chance of spawning before being caught. Variables pawning activity is known for pelagic species in Western African coast.

Studies on egg and larval distribution were conducted in the 1970s by Conand [6, 7] and Boëly *et al.* [8] and summarized by Garcia [9]. A first investigation on the distribution of fish larvae in the Senegalese sub-region revealed the importance of retention zones in conjunction with upwelling frontal zones along the coast to maintain high larval concentrations in the area [10]. But, more often, in such studies the abundance and distribution of ichtyoplankton are not spatially resolved to species level [11]. It is therefore important that new studies focusing on fish eggs and their spatio-temporal distribution along the West coast of Africa as well as their relationships to environmental forcing, need to be carried out to update knowledge that could serve as useful tool in developing a sound management plan.

This study was conducted on the Africa western coastal zone from Western Sahara to the Senegalese sub-region, a section of the Senegalese coastline south of Dakar, covering a range from 22.4 °N to 13.4 °N. This area is influenced by upwelling as the most southern part of the Canary upwelling ecosystem during the upwelling in season from autumn to spring, while in summer the area is strongly influenced by a decrease of the upwelling intensity through the influx of warm tropical waters from the Guinea Dome [12]. The study aimed at identifying the main spawning areas of the four economically important species round sardinella (*Sardinella aurita*), anchovy (*Engraulis encrasicolus*), European sardine (*Sardina pilchardus*) and horse mackerel (*Trachurus thrachurus*) during a cold and a warm period in the southern Canary Current Ecosystem.

2. Material and methods

2.1 Study area

The study area comprised a coastline of about 2000 kilometers (13.4°N- 22.4°N) from Western Sahara to Senegal (Figure 1).In general, the continental shelf off West Africa is less than 35 to 55km wide, except in the area between latitudes 24- 20° N, and the area between Dakar (16° North) and Freetown (8° North) where the shelf is up to about 160 km wide [13].

Two expeditions were conducted along to collect samples at 28 stations in summer 2014 (June 22 – July 7) and 56 stations in winter-spring 2015 (March 11 – 18).

2.2 Data collection

2.2.1 Environmental data

Salinity, temperature and fluorescence were measured using a CTD (conductivity, temperature, depth)-sampling probe (Seabird 911plus). Additional water samples were collected between surface and 5m above bottom to a maximum depth of 1000 m off the continental shelf to calibrate salinity measurements of the CTD probe. Downward cast data were binned to 5 m-intervals and mean surface values were calculated for salinity, temperature and fluorescence from 5 to 30 m depth. SST images from satellite measurements were obtained from the NASA EOSDIS Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory (Pasadena, CA).

2.2.2 Fish egg processing

Fish eggs were sampled using a modified high speed plankton Gulf VII sampler with a 280µm mesh. Double oblique tows collected eggs between surface and 200 m water depth. Ship speed was 5 knots and winch speed during shooting and retrieval was 0.7 m · s^{-1}. Plankton samples have immediately been fixed in a 4 % formaldehyde and freshwater liquid, and were transferred after a minimum of 24h of fixation into a nontoxic sorting fluid consisting of 0.5 vol.% propylene phenoxetol, 4.5 vol.% propylene glycol and 95 vol.% freshwater[14]. Fish eggs were sorted out under a dissection microscope.

Egg abundance was standardized according to:

$$Y = \frac{d \cdot x}{v}$$

where Y is the abundance (number of eggs m^{-2}), d the maximum catch depth (m), x the number of eggs collected, and v the filtered water volume (m^3) at each sampling station.

Indicator of abundance was calculated as the quotient between the species abundance and the average abundance. We considered spawning ground as important (primary spawning ground) for indicator value x_i/mean (x_i)>0.5.

2.2.3 Species-environment relationships

Generalized additive modeling (GAM) was used to correlate egg abundance and the environmental factors salinity, temperature, fluorescence and bottom depth. GAMs are in particular useful for non-linear relationships [15], and the model takes the form:

$Y_i = a + f(X_i) + e_i$

Where$a$ is a constant, e_i is the error term, Y_i is egg abundance, X_i represents an environmental factor and f denotes a smoothing function for X_i. The smoothing term is characterized by its empirical degrees of freedom (edf), which in the most simple case is set to 1.0 representing a linear regression. The GAM default setting of edf=1.0 as a minimum was overridden by the specification "cs" (R package mgcv), which firstly prevents forcing of linear regressions, and secondly allows to identify meaningless factors where edf is zero.

The interpretation of species-environment relationship requires a sound understanding of data structure. Abundance data greater than zero are in most cases not normally distributed, and in many cases abundance data are zero-inflated, i.e. more zeros are present than would have been expected from a specific distribution. Data are then called over-dispersed, i.e. variability is greater than expected by a distribution model. Excess zeros could be due to survey design by including uninhabited space, for instance oceanic regions where coastal species are not present. Alternatively to abundance distributions, species distributions may be described in term of presence-absence distributions [16], when environmental factors perform at ordinal (e.g. present in warm waters) rather than cardinal scale (e.g. peak abundance at 21.5 °C). Environmental factors may be correlated leading to the problem of collinearity in fitting parameter values. In order to address these uncertainties, four different GAMs are conducted [17]: (a) untransformed abundance data (b) log(y+1) transformations to reduce effect of non-normality in egg abundances, (c) log (y+1) transformed data of presences only to overcome over-dispersion, (d) presence-absence data with negative binomial error structure and logit link. Option (c) reduces the number of available cases and therefore was only applied for most dominant eggs (add species). For environmental factors, correlation structure is analyzed to evaluate collinearity. For each descriptive model, explained deviance (equivalent to explained variance) and p-values for factors significant at $p < 0.05$ are indicated. Analysis was performed using R software version 3.3.1. [18]

3. Results

3.1 Environmental data

The two seasons revealed a distinctly different pattern with regard to sea surface temperature (SST). In summer, SST varied between 18 °C and 30 °C (Figure 2a). Presence of cold-water indicates strong upwelling off Western Sahara and the Banc d'Arguin. Awarm water influx in the Mauritanian and Senegalese zone indicates the expansion of the Mauritania Current transporting warm water from the Guinea Dome northward. The warm water influx in summer hampers sub-surface water to be upwelled along the coasts. There were little correlations between the four selected environmental factors in summer (Table 1). A significant correlation was only found between chlorophyll and salinity (p=0.04).

During winter-spring 2015, coastal SST ranged between 15.5 °C and 21 °C (Figure 2b). This indicates the presence of upwelling that occurs along the Western coast of Africa during winter. The coldest waters were found along the coast from the Western Sahara to the Banc d'Arguin with temperatures of 16°C. Along the coasts of Mauritania and the Senegalese sub-region, upwelling was observed with SST of about 18°C. A significant correlation appeared for bottom depth and salinity ($p<0.05$) reflecting the interaction between sea surface salinity (SSS) and depth (Table 2).

3.2 Egg abundances and distribution

3.2.1 Total and unidentified eggs

During summer, fish eggs were patchily distributed along the study area. In some sampling stations particularly those situated more offshore, egg were frequently absent (Figure 3a). However, there were high abundances of eggs reaching respectively 327 and 398 eggs m-²in some stations between 22.5°-19°N in front of the Banc d'Arguin and the Western Sahara.

In winter-spring, fish eggs were recorded along the entire study area (Figure 3b). High abundances were observed off the Banc d'Arguin (21°-19°N) (maximum range 176 eggs m-²). Peak abundances occurred between 14.5°-13°N along the Senegalese sub-region with abundances ranging from 538 to 1779 eggs m-². It should also be noted that a significant amount of eggs was collected at station located at 14.5 °N, -17.2°W (Saint-Louis) with an abundance reaching 756 eggs m^{-2}.

In summer, unidentified eggs were, as was the case of total eggs, localized between 21°-19°N latitude (Figure 4a), i.e. in front the Banc d'Arguin and the Western Sahara with maximum abundance of 221.42 eggs m^{-2} at the point 22.49°N,17.28°W.

During winter-spring, the presence of unidentified eggs was recorded along the entire coastline (Figure 4b). In the northern section, eggs were distributed with a maximum abundances of 114 eggs m^{-2}between 21°-19.5°N latitude, whereas further south along the Senegalese coast, high concentrations of eggs were found between 13.72-14.12°Nlatitude and off the mouth of the river Senegal, at 16°N.

3.2.2 Species eggs

Figure 5 shows the abundance and distribution of eggs of four pelagic fish species along the Northwest African coast during summer (Figure 5a) and winter-spring (Figure 5b).

During summer, main spawning areas for *E. encrasicolis* were located along19-22°N in permanent upwelling zone (Western Sahara and the Banc d'Arguin) where egg abundances varied between 100 and 500 eggs m-².In winter-spring, most of the eggs were found in coastal upwelling zone, between 13.5°-14.5°N latitude, i.e. along the Senegalese sub-region, and to a lesser extent off the Banc d'Arguin (22.5°N, –17.2°W).Egg abundance peakedwith1000 to 1800 eggs m^{-2} during winter-spring at the Senegalese sub-region.

S. aurita eggs were observed in two stations off Mauritania during summer at 19.23°N, 16.68°W, and 16.16°N, -16.64°W. In winter-spring, eggs were found in three stations between 19°-17.7°N, i.e. in front of the Banc d'Arguin, and off the Senegalese sub-region at 14.12°N,-17.58°W, with <10 eggs m-².

T. trachurus eggs were found in low density during both seasons, at 20.06°N, 17°W during summer and in 10 stations in winter-spring between 19-22°N latitude, i.e. along the Western Sahara and the Banc d'Arguin.

S. pilchardus spawned in areas with strong upwelling between 22.5-20.5°N (in Western Sahara) in both summer and winter-spring, quantitatively ranging between 10 and 50 eggs m^{-2}.

3.3. Species- environment relationships

GAM models were run for both seasons, i.e. summer and winter-spring (Table 3).

For *S. pilchardus*, during summer (Figure 6a) no significant relationship could be found in the data set available in all four models. In case of Model 2 (Table 3), negative deviance was obtained indicating that the four factor model was in fact worse than any one of the original factors. During winter-spring, temperature correlated significantly with *S. pilchardus* egg abundances indicating an optimal SST of 17°C (Figure 6b).

The temperature partial plot of the GAM revealed an optimal temperature for *E. encrasicolus* spawning at16° to 17°Cduring summer (Figure 7a).The temperature effect was consistent between Model 1 and Model 2 in summer, and Model 2 and Model 3 in winter-spring. It was noted during the summer a significant relationship between egg abundance and temperature (p=0.034) in the Model 1 that explained 23.5% of the deviance (Table 3), and also in Model 2 (p=0.008; DE= 35.6%). In winter-spring (Figure 7b) strong relationship was found to temperature (p=0.008) and salinity (p=0.008) in Model 2, explaining 44.5 % of the total deviance. In addition, temperature relationship with abundance was significant in Model 2 (p=0.05, DE= 85.4%).

For *S. aurita*, only temperature had an impact on egg abundance during the summer in Model 1 (Table 3) (p=0.001; DE= 42.6%), whereas the most significant relationship to bottom depth in Model 2 was consistent for both summer (Figure 8a) and winter-spring (Figure 8b). A relatively significant influence of temperature during summer was notified thought the GAM plot with optimal temperature at 18°C. The Model 1 (Table 3) shown a strong relationship between temperature and abundance whereas the Model 2 show relationship with depth (p=0.015; DE= 31.4%) during summer.

For *T. trachurus*, the GAM plots shown no noticeable influence of environment factors on abundance and distribution of horse mackerel eggs during summer (Figure 9a), while in winter-spring important influence of chlorophyll was found at 1 mg/m³ and another stronger at 3mg/m³, indicating preference for intermediate chlorophyll concentrations (Figure 9b). Model 2 was significant during winter-spring explaining 54.7 % of the total deviance (Table 3).

4. Discussion

This study highlights the importance of coastal upwelling for spawning of commercially important species (Figure 5), but also for commercially less important and other species (Figure 3). The species examined in this study are important small pelagic species in West African coast that spawn at variable periods and areas. Sardine is a temperate-climate pelagic species, his optimum spawning temperatures were determined as 16-18°C for all north-west African regions [19]. In this study, the distribution of its eggs is thus limited in the area of permanent upwelling during the two seasons, for which a significant relationships was indicated in Model 2 with a reference to colder water masses of about 17 °C SST.A temperature effect was also indicated for anchovies, however with a preference for even colder waters of about 16.5 °C SST in winter-spring. These results are in consistent with the findings of Arbault and Boutin [20] carried out in the Bay of Biscay, showing that the most favorable temperature range for *E. encrasicolus* spawning was 15 to 25 °C. However, in northwestern Mediterranean during summer, the greatest egg abundance was found with surface water temperatures between 17 and 25°C [21]. Thus, egg abundance and distribution of *E. encrasicolus* show some differences with regard to the optimal area, season and habitat factors. Indeed, anchovies breeds throughout the year on the Senegalese-Mauritanian region [22], that explains in large part the high abundances of its eggs observed in our samples in both summer and winter-spring. Moreover, the main spawning season extend from April to October in the Mauritanian coastal waters [22], which is in support of the lower observed abundance in summer in this study (Figure 5). Low abundance observed in round sardinella and horse mackerel eggs could be explained by the low spawning intensity of these species during sampling periods. It has been shown that *S. aurita* breeds at all times of the year in off West Africa, but with distinct peaks, e.g. from about May off Senegal (but again in October November) through to July-August off Mauritania[23]. Our results further indicate, that round sardinella spawns in very shallow waters as indicated by the consistent Model 2 relationship in both seasons. For *T. trachurus*, as illustrated on the maps of spatial distribution of their eggs in the present study (Figure 5), breeding occurs mainly in winter [24], but principal spawning occurs in November-December and until January-February in northern Mauritania. In this study, *T. trachurus* showed preference for intermediate levels of primary production (Table 3).

Furthermore, our study showed that with regards to environmental variables such as temperature, salinity, chlorophyll and depth each species was markedly different indicating some influence on time, place and intensity of fish spawning. Indeed, significant influence was found between egg abundance and temperature for sardine, sardinalla and anchovies during summer, whereas during winter-spring a potential link was found mainly with bottomdepth and chlorophyll for sardine and horse mackerel in particular. More generally, in many studies, variation of temperature and water depth have been identified as important factors responsible for spawning and eggs distribution of pelagic fishes [25, 7, 23, 26].

As regard the spawning periods, studies have shown that the spawning activity of most pelagic species is maximal during the upwelling season. Moreover, Roy [27] has shown that in Senegal coastal area, unlike in Morocco zone, spawning and upwelling occur simultaneously. Indeed, the strategies adopted provide to adults and larvae optimal trophic conditions for breeding and larval survival leading to strong recruitment.

In relation with coastal environment, several studies have clearly identified the main breeding and spawning grounds of the most common species such as anchovy, sardine, horse mackerel, round sardinella, along the West African coast. Based on the work of Conand [6] who had studied on fish larvae distribution, these nursery habitats are located in Senegal-Mauritanian coast, and cover the area extending from the Banc d'Arguin to south of Cape Blanc between 18’30’’N to 21’N latitude and from South Peninsula Cape Verde to the coast of Sierra Leone in latitude 8’N to 14’30’’N. These essential breeding areas in near shore have a common topography; they are areas where the continental shelf is wide and thus constitute an area of coastal retentions that limits the dispersion of fish eggs and larvae offshore[28; 29].

Moreover, fish eggs scarcity recorded within stations offshore in this study could be explained by the low frequency of egg laying in those particular locations. According to Roy [29], in upwelling ecosystems, fish tend to avoid spawning in areas dominated by strong offshore transport and strong wind-mixing. This reinforces the idea that adult behavior would have a significant role, in particular by selecting areas and periods where oceanographic conditions are relatively stable and will improve retention of eggs and larvae, as well as food supply [30].

The location of spawning grounds in the West African coast was illustrated using thematic map to define primary and secondary spawning areas for each of the four species (Figure 10a) and for total eggs (Figure 10b). Then, important spawning areas were clearly localized in Western Sahara, in front the Banc d’Arguin, in Saint-Louis and along the Senegalese sub-region. The importance of these areas for spawning adult’s distribution has already been observed by a number of authors [31; 32; 27; 33; 10]. Thematic maps performed by Garcia [31] have recognized Banc d’Arguin and Petite-Cote as spawning areas for *S. aurita* and the area extend from Western Sahara to Banc d'Arguin for *T. trachurus*. For *E. encrasicolus*, the map shown the highest eggs density, in compliance with several studies that suggest a wide spawning period and area that would be due to the temporal difference in the spawning of different cohorts [29].

Table 1: Correlations and respective p-values between environmental factors during summer 2014

Factor correlations and p-values	Mean temp.	Mean sal.	Mean chloro.	Bottomdepth
Mean temperature		p=0.25	p=-0.12	p=0.24
Mean salinity	0.25		p=0.04	p=0.16
Mean chlorophyll	-0.12	0.04		p=-0.20
Bottomdepth	0.24	0.16	-0.20	

Table 2: Correlations and respective p-values between environmental factors during winter-spring 2015

Factor correlations and p-values	Mean temp.	Mean sal.	Mean chloro.	Bottomdepth
Mean temperature		p=0.12	p=-0.24	p=0.75
Mean salinity	0.12		p=0.13	p=0.049
Mean chlorophyll	p=-0.24	0.13		-0.12
Bottomdepth	p=0.75	p=0.049	-0.12	

Table 3: Influence of environmental factors on the abundance and distribution of pelagic eggs, summer 2014 and winter-spring 2015.DE: Deviance explained, significant factor indicated at *p*<0.05, MTEMP – mean temperature 0-30 m, MSAL - mean salinity 0-30m, BDEPTH-bottom depth

Species	Model 1 Untransformed Deviance explained and significant factors	Model 2 Log(Y+1) incl. Absences	Model 3 Log(Y+1) presence data	Model 4 Presence-absence data
		Summer		
Sardinapilchardus	DE= 7.96%	DE= -4.17%	NA	DE= 28.1%
Engraulisencrasicolus	DE.= 23.5% MTEMP p=0.034	DE= 35.6% MTEMP p=0.008	NA	DE= 66.9%
Sardinellaaurita	DE.= 42.6% MTEMP p= 0.001	DE= 31.4% BDEPTH p= 0.015	NA	DE= 31.9%
Trachurustrachurus	DE= 0.0007%	DE= 53.6%	NA	DE= 0.0009%
		Winter-Spring		
Sardinapilchardus	DE=26.3%	DE=41.8% MTEMP p=0.004	NA	DE=100%
Engraulisencrasicolus	DE.=24.0%	DE=44.5% MTEMP p=0.018 MSAL p=0.011	DE=85.4% MTEMP p=0.05	DE=55.4%
Sardinellaaurita	DE.=2.18%	DE=54.5% BDEPTH p=0.03	NA	DE=74.6%
Trachurustracharus	DE=11.3%	DE=54.7 MCHLO p=0.017 BDEPTH p=0.04	NA	DE=64.1%

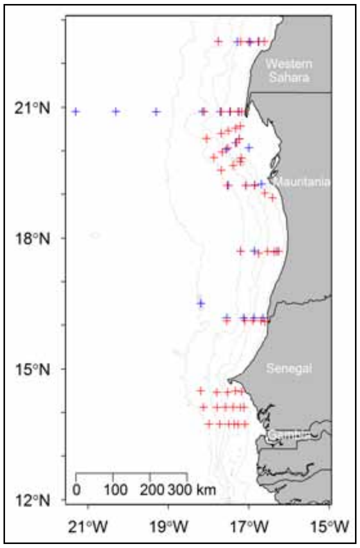

Fig 1: Map showing the location of sampling stations along the West African coast of the summer cruise (+) in 2014 and winter-spring cruise (+) in 2015

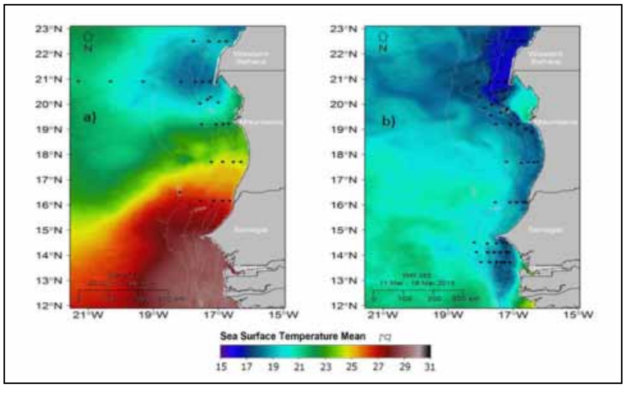

Fig 2: Horizontal distribution of mean sea surface temperature (SST), (a) during summer 2014 and (b) winter-spring 2015(JPL OurOcean Project 2010).

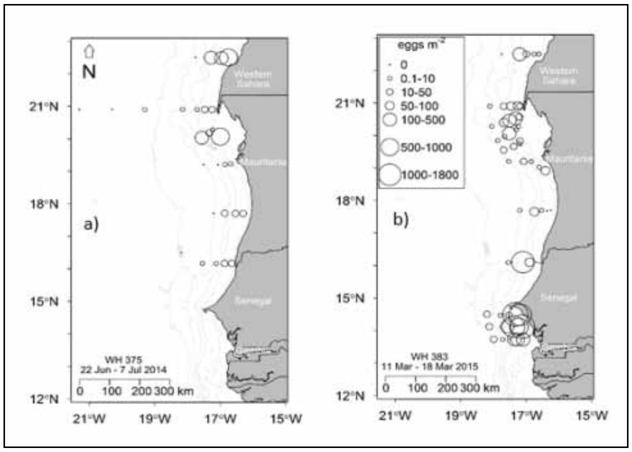

Fig 3: Map showing the abundance (no. eggs m-²) and horizontal distribution of total fish eggs along the West African coast during (a) summer 2014 and (b) winter-spring 2015, size of bubbles depicts egg abundance.

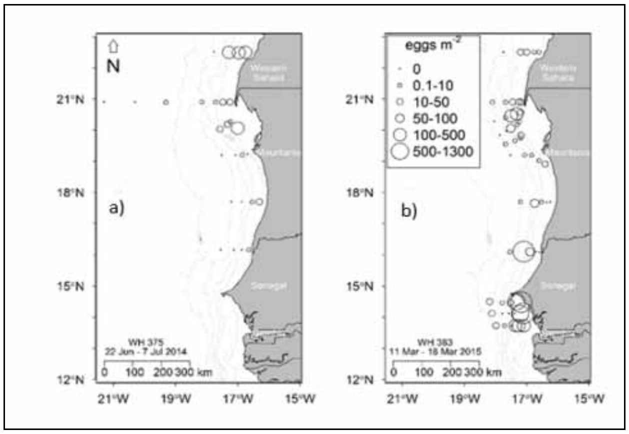

Fig 4: Map showing theabundance (no. eggs m-²) and horizontal distribution of unidentified fish eggs along the West African coast during (a) summer 2014 and (b) winter-spring 2015, size of bubbles depicts egg abundance.

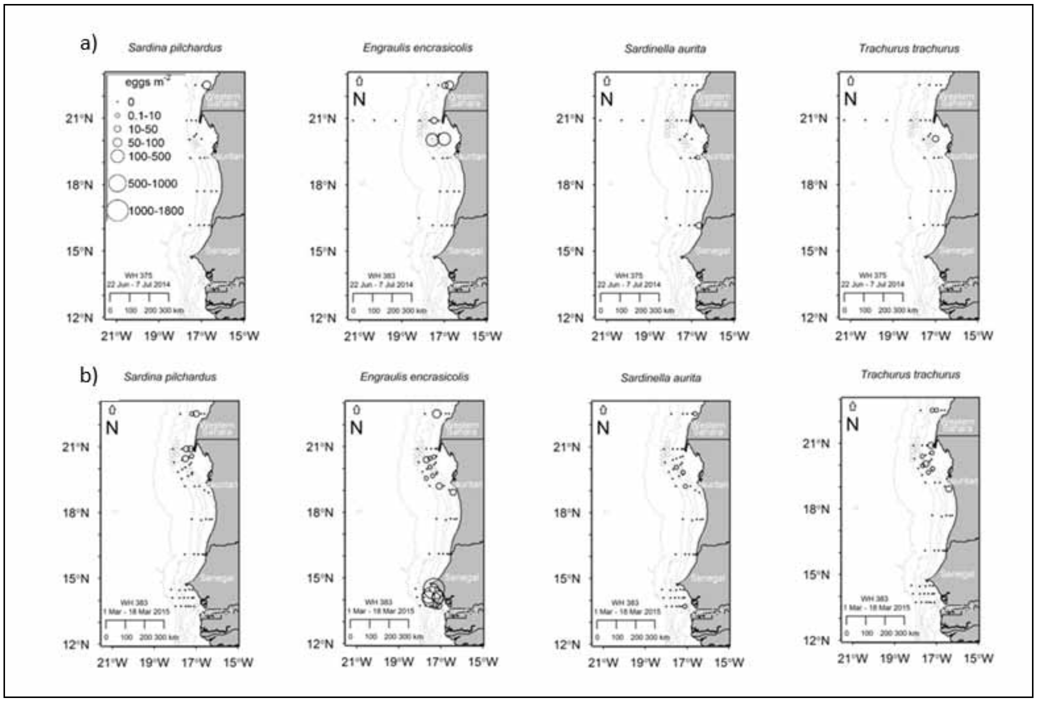

Fig 5: Map showing the abundance (no. eggs m-²) and horizontal distribution of pelagic fish eggs along the West African coast during (a) summer 2014 (Jun-Jul) and (b) winter-spring 2015 (Mar).

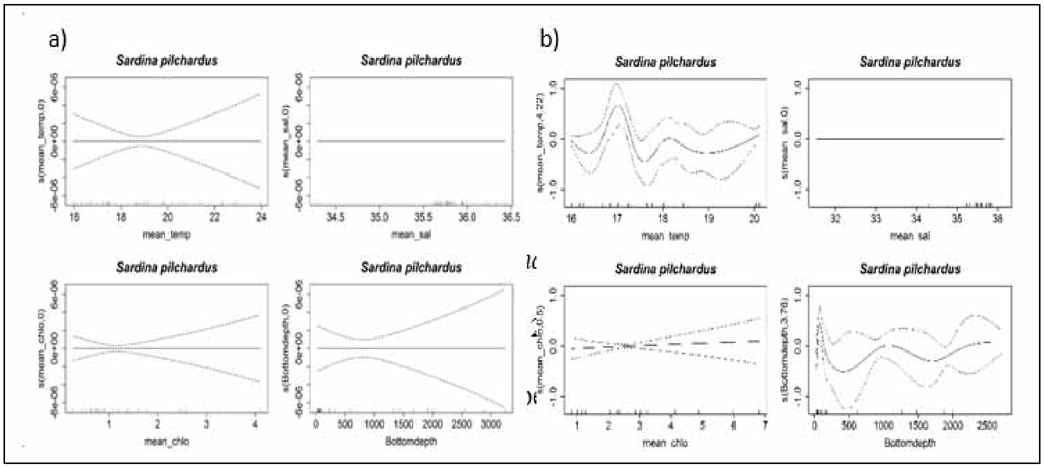

Fig 6: GAM Model 2 plots for *Sardina pilchardus* showing the additive effects of abiotic factors on eggs abundance during (a) summer 2014 and (b) winter-spring 2015. See Table 3 for model specifications.

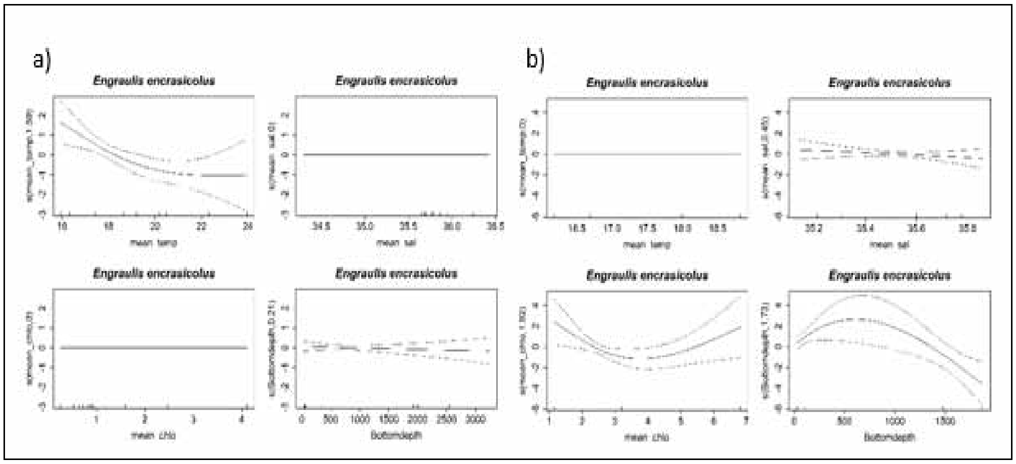

Fig 7: GAM Model 2 plots for *Engraulis encrasicolus* showing the additive effects of abiotic factors on eggs abundance during (a) summer 2014 and (b) winter-spring 2015. See Table 3 for model specifications.

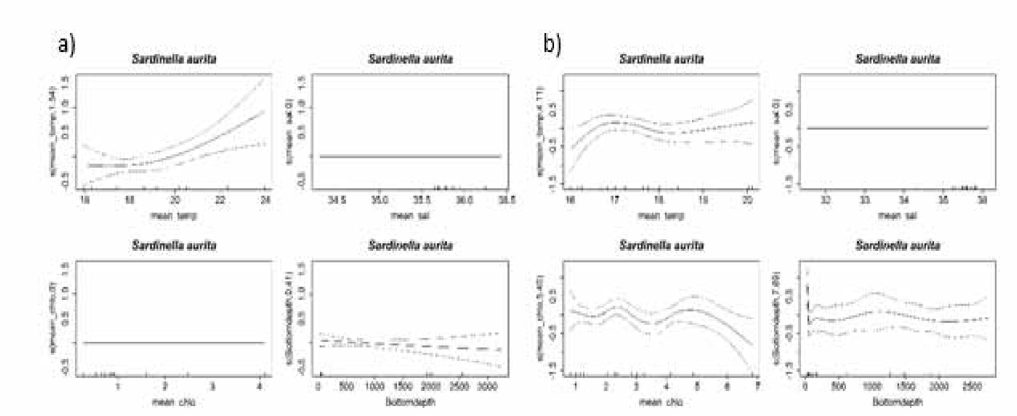

Fig 8: GAM Model 2 plots for *Sardinella aurita* showing the additive effects of abiotic factors on eggs abundance during (a) summer 2014 and (b) winter-spring 2015. See Table 3 for model specifications.

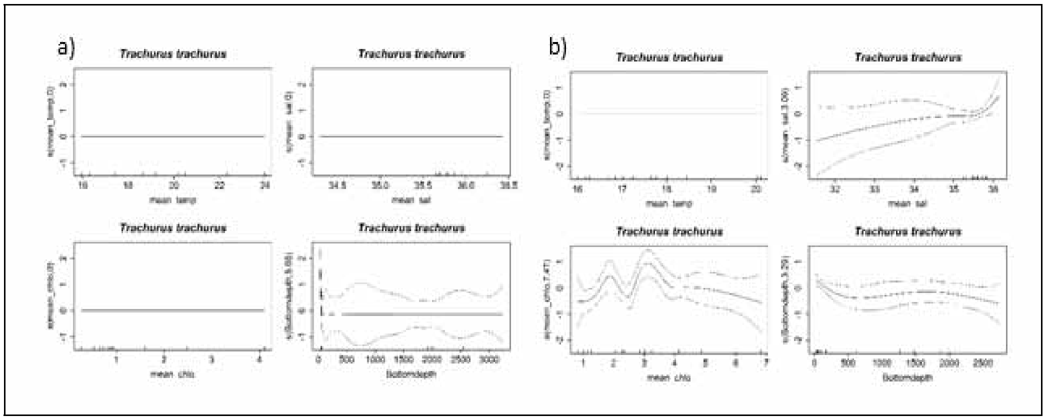

Fig 9: GAM Model 2 plots for *Trachurus trachurus* showing the additive effects of abiotic factors on eggs abundance during (a) summer 2014 and (b) winter-spring 2015. See Table 3 for model specifications.

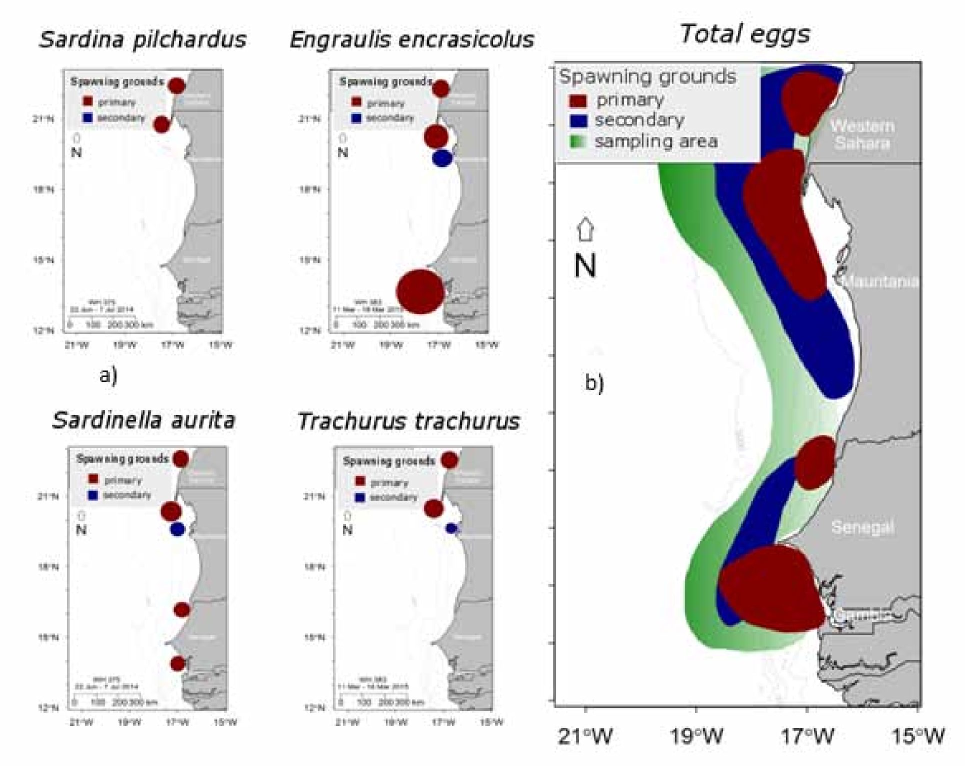

Fig 10: Localization of spawning grounds for the four selected species (a) and total eggs (b); the map of fish eggs abundance and repartition were exported into Inkscape software (Inkscape for Desktop, Software Version 0.92.1) to draw the spawning grounds.

5. Conclusion

The West-African coasts of the Canary Current ecosystem are an important spawning ground for numerous species because of the influence of the Canary upwelling system and the topography of the area. Environmental variables such as temperature but also chlorophyll and depth can strongly influence reproduction activities of adult's individuals and eggs distribution patterns. Moreover, hydrographic profile and egg stage are key information necessary in order to understand and predict eggs abundance and distribution and to understand climate change adaptation strategies of pelagic fish species.

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