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## Long term changes in life history traits and catches of the round sardinella, *Sardinella aurita* (Clupeidae), along the Senegal coast, West Africa

Samba Ousseynou <sup>1,\*</sup>, Diouf Khady <sup>1</sup>, Fall Massal <sup>2</sup>, Ndiaye Papa <sup>1</sup>, Panfili Jacques <sup>3</sup>

<sup>1</sup> Laboratoire de Biologie Marine, LABEP-AO, IFAN-Ch. A. Diop, BP, 206, Dakar, Senegal

<sup>2</sup> Institut Sénégalais de Recherches Agricoles (ISRA)/Centre de Recherche Océanographique de Dakar-Thiaroye (CRODT), Dakar, Senegal

<sup>3</sup> IRD, MARBEC, Univ Montpellier-IRD-Ifremer-CNRS, Place E. Bataillon, cc093, 34095 Montpellier, France

\* Corresponding author : Ousseynou Samba, email address : [ousseynou0303@gmail.com](mailto:ousseynou0303@gmail.com)

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### Abstract :

The main life history traits of the round sardinella, *Sardinella aurita* Valenciennes 1847 were updated in Senegalese coastal waters, together with an evaluation of the captures over the last 33 years (1981-2013). In the context of global change and an increase in the average sea surface temperature along the Senegalese coast, most of the life history traits of *S. aurita*, such as condition factor, period of reproduction, egg sizes, relative fecundity and growth did not change significantly over the years. In contrast, the size at first sexual maturity and the absolute fecundity increased significantly, and current catches recorded less large individuals. The growth was rapid and very variable, with a longevity estimated at 6-7 years.

These updated data for life history traits show that the round sardinella was fully exploited in the area, that the fishing effort for this species should be reduced, and that the minimum size (120 mm) authorized by the Senegalese fisheries code should be increased (185-200 mm) to maintain stocks along the Senegal coast.

### Highlights

► Condition factor of the round sardinella is a very good indicator. ► Reproductive pattern has not changed for more than 40 years ago. ► The reading of the otoliths gave a good estimate of the age and growth. ► Growth was rapid and variable with longevity of 6–7 years. ► Decline in landings could be related to the reduction in the annual number of trips.

**Keywords** : condition factor, reproductive pattern, age, growth, otolith, *Sardinella aurita*

## 1. Introduction

A global increase in fishing pressure on small pelagic fish stocks has been observed over the past two decades which could have a significant impact of the sustainability of exploitation of these stocks (Naylor et al., 2009; Tacon and Metian, 2009). Among these small pelagic species, the sardinellas (Clupeidae), *Sardinella aurita* Valenciennes 1847 and *Sardinella maderensis* Lowe 1838, play an important ecological role in coastal ecosystems and are strongly targeted by the fisheries in Northwest Africa (NWA), Morocco, Mauritania and Senegal (Fréon et al., 1978; Braham et al., 2014). The sardinella catches in NWA account for 26% (398,000 tons per year) of the total catch of small pelagic fish, 72% of these are *S. aurita*, the round sardinella (FAO, 2017). This species has been intensively exploited for decades, and is crucial to the economies of NWA. Most of the resources based on small pelagic fish, such as the round sardinella, are today fully exploited or even overexploited because of the strong demand for this low-cost protein source (FAO, 2017).

In Senegal, the life history traits of *S. aurita* were described for the first time by Blanc (1950), and then Postel (1955), and some reproductive and growth traits were published in the late 1970s and early 1980s (Boëly et al., 1978; Boëly, 1982; Boëly et al., 1982a; Boëly et al., 1982b). Empirical analysis of data collected more than 30 years ago have shown that the trophic migrations and the life history traits of the species are influenced by seasonal and inter-annual climate variations (Cury and Fontana, 1988; Roy et al., 1989).

48 It is, therefore, important that we update our knowledge of the main life history traits  
49 of the round sardinella to give a better indication of the stocks and improve their management.  
50 Firstly, the present study assessed the current stocks using a comparative analysis of the  
51 changes in landings and the fishing effort over a 33-year period in Senegal (1981-2013).  
52 Secondly, a sampling campaign in 2012-2013 updated our knowledge of the main life history  
53 traits of the round sardinella along the Senegalese coast. This traits included the condition  
54 factor, the reproduction (time and duration of the spawning season, reproductive cycle,  
55 gonado-somatic index, size at first sexual maturity, fecundity, and ovocyte size) and the  
56 growth / age curve (using otolith growth increments). Thirdly, these data were compared with  
57 previous data from the same area and other areas to determine possible changes in the traits  
58 that may be related to significant biological or environmental pressures. Finally, based on  
59 changes in life history traits and the changes in catches, we drew up recommendations for the  
60 future management of the fisheries to ensure the sustainability of the fish stocks.

## 61 2. Material and methods

62 The annual records of round sardinella catches (in tons) and fishing effort (trips by  
63 fishing units) in Senegalese waters between 1981 and 2013, were provided by the  
64 Oceanographic Research Center, Dakar-Thiaroye (CRODT). These data were obtained mainly  
65 from landing surveys at Saint Louis, northern Thiès, Cape Verde and southern Thiès, based on  
66 catches by local fishermen using canoes (Fig. 1). The fishing areas were located between 13 °  
67 30 N and 16 ° 04 N at varying distances from the shore and in shallow water (between 20 and  
68 70 m). The number of trips by fishing units was recorded on a daily basis by CRODT,  
69 whereas landing data were collected randomly on about 5 days per week. After sorting the  
70 data by port, gear type and period (fortnightly intervals), total landings per port were  
71 estimated by multiplying the mean number of fish landed for the sampled trips by the total  
72 number of fishing trips made and catches were summed by month for each landing port.

73 Samples of round sardinella were collected and the sea surface temperature (SST)  
 74 recorded monthly, from July 2012 to June 2013, at the three main landing locations at Hann  
 75 bay (Cape Verde peninsula), Mbour and Joal in Senegal. Samples from the landings, fresh but  
 76 already dead, were kept on ice during transfer to the laboratory, where fork length ( $FL$  in  
 77 mm), total body weight ( $W$  in g) and eviscerated weight ( $W_e$  in g) were measured. Sex was  
 78 determined with a macroscope using Fontana's scale (1969) and gonads were weighed ( $W_g$  in  
 79 g). The otoliths (*sagittae*) were extracted, cleaned in water, dried and stored dry in labeled  
 80 microtubes.

81 The condition factor ( $Cf$ ) was calculated for each individual using the formula:

$$82 \quad Cf = 10^5 \times W/FL^3 \quad (1)$$

83 The non-parametric Mann-Whitney test was used to compare mean  $Cf$  between months  
 84 because the data were not suitable for parametric tests. The gonado-somatic index ( $GSI$ ) was  
 85 calculated for each month to determine the reproductive period, using the formula:

$$86 \quad GSI = 100 \times W_g/W_e \quad (2)$$

87 The mean  $GSI$  was compared between months for a given sex using a non-parametric Mann-  
 88 Whitney test. The size at first sexual maturity ( $FL_{50}$ ), where 50% of individuals of that size  
 89 were mature during the reproductive period, was calculated using 50 mm size classes.  $FL_{50}$   
 90 was estimated using a logistic function

$$92 \quad \%M = 100/[1 + \exp^{-a(FL-FL_{50})}] \quad (3)$$

93 where  $\%M$  is the percentage of mature fish in each fork length class,  $FL$  is the central value of  
 94 each fork length class and  $a$  and  $FL_{50}$  are constants determined by non-linear regression

95 (quasi-Newton method, Statistica ®). The size at first sexual maturity were compared  
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 3 96 between sampling locations using Student *t* test.

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 5 97 The fecundity was calculated from female gonads of at least stage V during the  
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 7 98 spawning period (Fontana, 1969). For each female, both gonads were weighed and a sub-  
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 9 99 sample was taken from one of the gonads and placed in Gilson's fluid (100 ml ethanol, 9 ml  
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 11 100 glacial acetic acid, 20 ml of 60% nitric acid, 20 g mercury (II) chloride and 875 ml distilled  
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 13 101 water). The ovocytes were separated in Gilson's fluid and then counted manually under a  
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 15 102 binocular microscope. The absolute fecundity ( $F_A$ ) was calculated as the number of ovocytes  
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 17 103 to be released at the next spawning and the relative fecundity ( $F_R$ ) as the ratio of the absolute  
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 19 104 fecundity to the individual fish weight (Fontana and Pianet, 1973).

$$105 \quad F_A = W_g \times N_{ov} / W_{gs} \quad (4)$$

$$106 \quad F_R = F_A / W \quad (5)$$

31  
 32 107 where  $N_{ov}$  is the number of ovocytes in the subsample,  $W_g$  is the total weight of the gonad and  
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 34 108  $W_{gs}$  is the weight of the gonad subsample. To measure the ovocytes, five images were taken  
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 36 109 of each gonad (Leica LAS-EZ software) and the diameter of each ovocyte was measured  
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 38 110 automatically using the Image J freeware. The means were compared between sampling  
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 40 111 locations using ANOVA.

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 42 112 A standard protocol was used to interpret the growth bands on otoliths. An image of  
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 44 113 the whole right otolith immersed in 95% ethanol was recorded with a binocular microscope  
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 46 114 under reflected light against a dark background. Each otolith was interpreted three times, first  
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 48 115 from the core to the rostrum margin, and then from the core to the posterior margin, and then  
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 50 116 from the posterior margin to the core. Seasonal translucent bands were identified and counted  
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 52 117 (Fig. 2). The last translucent band was not counted if it was located on the otolith margin and,  
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 54 118 therefore, still in formation. If at least two of the three readings (i.e. number of translucent  
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119 bands) agreed, these readings were used to calculate the age (in months). If there was no  
 120 agreement between any of the readings, then the otolith was rejected. The consistency of the  
 121 growth band counts was assessed by calculating the Chang's coefficient of variation (1982),  
 122 with a target of less than 5%, based on the recommendation of Campana (2001) and using the  
 123 formula:

$$CV_j = 100 \times \frac{\sqrt{\frac{\sum_{i=1}^R (X_{ij} - \bar{X}_j)^2}{R-1}}}{\bar{X}_j} \quad (6)$$

127 where  $CV_j$  is the coefficient of variation of the age estimated for the  $j^{\text{th}}$  fish;  $X_{ij}$  is the  $i^{\text{th}}$  age  
 128 estimation of the  $j^{\text{th}}$  fish,  $\bar{X}_j$  is the mean age of the  $j^{\text{th}}$  fish, and  $R$  is the number of times the age  
 129 was estimated. To determine when the translucent bands were deposited and validate the age  
 130 estimates, the percentage of translucent otolith margins was calculated for each month over a  
 131 year. The growth curve was represented by the Von Bertalanffy (1938) growth function  
 132 (VBGF) fitted using non-linear regression to minimize the residual sum of squares  
 133 (Statistica®):

$$FL = FL_{\infty} (1 - \exp^{-K(t-t_0)}) \quad (7)$$

135 where  $FL$  is the fork length at time  $t$ ,  $FL_{\infty}$  is the asymptotic fork length,  $K$  is the growth  
 136 coefficient and  $t_0$  is the theoretical time at which the length would be zero. These growth  
 137 parameters were compared between locations using a weighted least-squares likelihood ratio  
 138 test (Kimura, 1980). For  $k$  populations, the likelihood ratio test ( $S_{LR}$ ) was used with 3 degrees  
 139 of freedom (3 parameters):

$$S_{LR} = \sum_{i=1}^k n_i (\ln S_c^2 - \ln S_k^2) \quad (8)$$

where  $n_i$  is the number of individuals in the  $k^{\text{th}}$  population,  $S_c^2$  is the residual variance of the pooled model (for all populations), and  $S_k^2$  is the residual variance of the models of each of the  $k$  populations. The same likelihood ratio test was used for pairwise comparison of the growth models. The growth parameter estimates this same species were compared with those of other authors using the performance index ( $\Phi'$ ) proposed by Pauly and Munro (1984):

$$\Phi' = \log K + 2 \times \log FL_{\infty} \quad (9)$$

### 3. Results

#### 3.1. Catches and fishing analysis

There were four main phases in round sardinella catches in Senegal over the 33-year period (Fig. 3a). From the early 1980s to the early 1990s, there was a gradual increase in catches, from 25,000 to around 60,000 tons. During the 1990s, round sardinella landings doubled. There was a peak in 1994 (around 124,000 tons), and then a decline before stabilizing in 1999-2003 (around 60,000 to 90,000 tons). From 2003, landings increased rapidly reaching a second, more sustained, peak in 2008 (around 390,000 tons), about three times the 1994 peak, and then the landings declined progressively until 2013 (135,000 tons). Catches were dominated by purse seine fishing (98%) and only a very small quantity (2%) was caught using other types of fishing gear. A comparison of the quantity of fish landed with the fishing effort shows that catch was directly related to purse seine fishing effort over the 33-year period (Fig. 3b). Breaking down the annual fishing effort into the types of fishing gear showed that set gillnets were the main type of gear used (50% of the total number of trips), followed by purse seines (41% of the total number of trips). Encircling gillnets, beach

163 seines and other types of fishing gear were rarely used for catching round sardinella (9% of  
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2 164 the total number of trips).  
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### 6 165 3.2. Condition factor

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9 166 At Hann, the highest mean values of condition index ( $Cf$ ) were during the cold season  
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11 167 (February to May), with a peak in April, and a progressive decrease was observed from July  
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13 168 to September, with the lowest  $Cf$  in August (Fig. 4a). The mean values of  $Cf$  in February,  
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15 169 March and May were statistically identical (Mann-Whitney,  $p > 0.05$ ), and were significantly  
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17 170 higher than all other months except April (Mann-Whitney,  $p < 0.05$ ). At the southern sites  
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19 171 (Mbour and Joal), the period with higher condition factors was longer than at Hann (Fig. 4),  
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21 172 lasting for six months (January to July). The mean values of  $Cf$  were also significantly lower  
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23 173 from August to December, with the lowest values in August at Joal and in October at Mbour  
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25 174 (Figs. 4b, c; Mann-Whitney,  $p < 0.05$ ).  
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### 32 175 3.3. Reproduction

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35 176 At Hann, the female and male  $GSI$ s showed that there were two reproductive periods  
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37 177 with different amplitudes each year: the first was from February to March, and the second was  
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39 178 from October to November (Fig. 5a). Comparing the female  $GSI$ s between months showed  
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41 179 that the  $GSI$  in October was significantly different to all other months, except November  
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43 180 (Mann-Whitney,  $p = 0.83$ ). For males, the  $GSI$  in October was statistically identical only to  
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45 181 September, November and December (Mann-Whitney,  $p > 0.05$ ). At Mbour, the female  $GSI$ s  
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47 182 were highest between January and April, with a peak in February, then decreasing to the  
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49 183 lowest value in June (Fig. 5b). From July to December, the  $GSI$ s were relatively low. The  
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51 184 female  $GSI$ s in February were statistically identical to those in January, March, April and  
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53 185 November (Mann-Whitney,  $p > 0.05$ ). The male  $GSI$ s were similar to those of the females,  
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55 186 with a highest value in March (Fig. 5b). The  $GSI$  in March was statistically identical only to  
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187 November (Mann-Whitney,  $p > 0.05$ ). At Joal, the female *GSI*s were comparable to that of  
188 Mbour during the cold season, then increased and reached higher values from August to  
189 November (Fig. 5c). The female *GSI*s in February was statistically identical to those of  
190 January, March, August, September, October and November (Mann-Whitney,  $p > 0.05$ ). The  
191 male *GSI*s showed three significant peaks in January, March and November (Fig. 5c). The  
192 pattern of male *GSI*s was similar to that of the female *GSI*s, with March being different from  
193 all other months (Mann-Whitney,  $p < 0.05$ ).

194 The *GSI*s showed that, at Hann, *S. aurita* had a single main reproductive period which  
195 lasted from October to November. This might be followed by a lesser secondary reproductive  
196 period from February to March. At Mbour and Joal, there were two reproductive periods, the  
197 first from January to March-April and the second in November at Mbour and from August to  
198 November at Joal.

199 At Hann, the *FL* of mature individuals ranged from 97 mm to 307 mm for females and  
200 from 117 mm to 292 mm for males. The size at first sexual maturity ( $FL_{50}$ ) was 225 mm for  
201 females and 181 mm for males (Figs 6a, b). At Mbour, the smallest mature female was 149  
202 mm and the smallest male was 146 mm, while the largest mature females and males were 300  
203 mm. The  $FL_{50}$  was 218 mm for females, and 200 mm for males (Figs 6c, d). At Joal, the *FL*s  
204 of the smallest mature fish were close to those at Mbour: 143 mm for a female and 152 mm  
205 for a male. The largest fish were 296 mm and 291 mm and  $FL_{50}$  was 219 mm for females and  
206 206 mm for males (Figs. 6e, 6f). For all sites together,  $FL_{50}$  was larger for females than for  
207 males (Student  $t = 3.19$ ;  $df = 4$ ;  $p = 0.03$ ).

208 The mean absolute and relative fecundities of *S. aurita* were very high with a high  
209 variability between individuals (Table 1). The fecundities seemed to decrease from Hann to  
210 Joal, but were still high and the eggs released were small. There were no statistical differences

211 in fecundities and egg size between Mbour and Joal ( $p>0.05$ ; Table 1). Absolute and relative  
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2 212 fecundities at Hann were significantly higher than at Mbour and Joal ( $p<0.05$ ; Table 1).  
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### 6 213 3.4. Age and growth

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9 214 We were able to read the translucent growth bands from the core to the edge of the otolith  
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11 215 posterior face. 13.7% of the otoliths were difficult to interpret, mainly because they were very  
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13 216 opaque, making it impossible to estimate their age. It was sometimes difficult to determine  
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15 217 whether the edge of an otolith was translucent or opaque because of the light reflection at the  
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17 218 edge, and these otoliths were excluded from the analysis. The age estimates had a coefficient  
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19 219 of variation of 2.41%. The monthly variation in the fraction of otoliths with translucent edges  
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21 220 showed that the bands were formed annually (Fig.7). This fraction reached a minimum in  
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23 221 December and peaked in June when the translucent band was deposited. The age in months  
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25 222 was then calculated taking into account the average birth date obtained from the *GSI* (October  
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27 223 for Hann, February for Mbour and Joal), the month when the translucent band was deposited  
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29 224 (June), the date of capture, and the number of translucent bands in the otolith. The growth  
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31 225 curves using the age estimates from the otoliths were highly variable (Fig. 8). The  
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33 226 coefficients of determination ( $R^2$ ) of the VBGF models were 0.70 for Hann and Mbour, and  
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35 227 0.64 for Joal. The growth was rapid for this species, especially at the beginning of life,  
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37 228 individuals reaching 100 mm in only few months, with a short life (6-7 years). The estimated  
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39 229 asymptotic fork lengths were 304 mm at Hann, 316 mm at Mbour and 340 mm at Joal (Table  
40  
41 230 2). The growth models were not significantly different between locations ( $S_{LR}<\chi^2=7.82$  for  
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43 231 3df,  $\alpha = 0.05$ ). The growth performance index ( $\Phi'$ ) was higher at Hann, showing that growth  
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45 232 was faster in this area, but older fish were found in southern Senegal (Table 2).  
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## 234 4. Discussion

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### 235 4.1. Round sardinella catches and fishing effort

236 The decline in landings of the round sardinella could be in part related to the  
237 noticeable reduction in the annual number of fishing trips (Fig. 3). The main causes could be  
238 socio-economic constraints after two major events. The first was the devaluation of the local  
239 currency (FCFA) in January 1994. As a result of the widespread inflation at the beginning of  
240 the 90s, prices for fishing gear and products surged (Creevey et al., 1995). To maximize the  
241 return on their fishing effort, many pelagic fishing units (particularly purse seines and  
242 encircling gillnets) converted to demersal fishing (Dème and Kebe, 2000). The second event,  
243 in 2008, was the result of sharp fluctuations in oil prices and exchange rates (Aloui et al.,  
244 2012). This oil shock, coupled with the remoteness of the fishing zones, seriously affected the  
245 Senegalese artisanal fishing sector, and particularly those using purse seine nets, which are the  
246 preferred gear for catching gregarious species. During this period, Senegalese canoes were  
247 used for organized illegal emigration and the departure of young fishermen had increased the  
248 shortage of fish in the markets and the artisanal fishing ports (Ba and Ndiaye, 2008).

249 The fluctuations in sardinella catches could also be caused by environmental changes  
250 and constraints arising from these changes. The abundance of small pelagic fishes in most  
251 parts of the world is controlled by hydrographic parameters and changes in the global or  
252 regional climate are likely to affect pelagic fish stocks and their fisheries (Kellogg and Gift,  
253 1983; Ramos et al., 1996; Ware and Thomson, 2005; Zeeberg et al., 2008; Braham et al.,  
254 2014; Thiaw et al., 2017). New studies carried out in the same area have shown the existence  
255 of distinct ranges of sea surface temperature, upwelling intensity, wind-induced turbulence,  
256 concentration of chlorophyll-a and north Atlantic oscillation index that are associated with the  
257 successful recruitment and abundance of *S. aurita* in Senegalese waters and Mauritanian  
258 waters (Zeeberg et al., 2008; Diankha et al., 2018). A depletion of phytoplankton biomass is

259 usually associated with ocean warming (Richardson and Schoeman, 2004), even if this is  
1  
2 260 moderate and spatially restricted to Mauritania and Senegal from 1998 to 2014 (Demarcq and  
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5 261 Benazzouz, 2015). Therefore, such changes might influence the recruitment success and  
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7 262 abundance of small pelagic fish populations such as *S. aurita*.

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9 263 Round sardinella catches fluctuated strongly over the 33-year period. Various hypotheses  
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12 264 could explain these fluctuations, but a single hypothesis cannot explain all of them. Socio-  
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14 265 economic, environmental and ecological pressures could all explain the fluctuations and  
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17 266 decline in catches. The fishing effort has reached a very high level and the population of this  
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19 267 species is may be not able to support such a high fishing pressure, given the climate changes  
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22 268 that have affected this area for decades.

#### 25 269 4.2. Condition factor

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28 270 The condition factor of the round sardinella along the Senegalese coasts showed an  
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31 271 annual cycle which is related to the seasons in this area. The life cycle of sardinellas is  
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33 272 directly influenced by environmental conditions, the metabolic activity being higher in the  
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36 273 cold season, and was directly reflected in the condition factor in the present study. The cold  
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38 274 season corresponds to the presence of nutrient rich waters and higher plankton abundance,  
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41 275 associated with the upwelling in Senegalese coastal waters (Nieland, 1982; Baldé et al.,  
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43 276 2019). The abundance of food during the cold season directly influences the weight gain of  
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45  
46 277 the pelagic fish. The periods of higher *Cf* for *S. aurita* were generally longer in the south (6  
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48 278 months) than in the Cape Verde peninsula (about three months). This difference between  
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51 279 central and southern Senegal could be due to the quantity and/or quality of food available in  
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53 280 the different environments (Diouf, 1991). Off the Cape Verde peninsula, the upwelling is  
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55 281 much less stable and disappears earlier than in the other areas (mid-April instead of mid-  
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58 282 May), as soon as the winds begin to turn northwestwards (Teisson, 1983). The southern  
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60 283 region is a feeding ground which has stronger upwelling in the cold season, making it more

284 favorable sardinella growth (Boëly et al., 1982a). Sardinellas remain concentrated in the  
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2 285 convergence zone, which shifts further south with stronger upwelling (Teisson, 1982; Binet,  
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4 286 1988). The condition factor of the round sardinella is, therefore, a very good indicator of the  
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7 287 seasonality in the area.  
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#### 11 288 4.3. *Reproduction*

14 289 At Hann, the main reproductive period was in the transition from warm to cold  
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16 290 seasons (October-November), just before the upwelling period. At Joal and Mbour, the second  
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19 291 reproductive period (November) was at the beginning of the upwelling period (Wooster et al.,  
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21 292 1976; Samb and Mendy, 2004). In the Mediterranean sea, spawning has been reported as  
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24 293 starting when there is an increase in the sea surface temperature (SST) to 22 °C or 25 °C  
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26 294 (Palomera and Sabatés, 1990; Mustačić and Sinovčić, 2012) or, in Northwest Africa, with a  
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29 295 reduction below 25 °C (F. Conand, 1977; Longhurst and Pauly, 1987) and Ghana (Quatey  
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31 296 and Maravelias, 1999). These differences were probably related to a preferred temperature  
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34 297 range for spawning and may be the explanation for the migration pattern of *S. aurita* along the  
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36 298 West African coast (Boëly et al., 1982a; Garcia, 1982). On the other hand, Bakun (1996) used  
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38 299 a comparative approach to define the three requirements ("triad") that were necessary for a  
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41 300 habitat to be suitable for the reproduction of pelagic fish: enrichment (upwelling, mixing,  
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43 301 etc.), concentration and retention of fry in a suitable habitat. It seems that the southern  
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45 302 Senegalese coast meets ecological requirements for *S. aurita* more closely and the results for  
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48 303 Joal show the whole reproduction cycle in Senegal. *S. aurita*, like most other Clupeids that are  
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50 304 highly vulnerable to changes in environmental conditions, is an opportunistic species that  
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53 305 reacts and adapts to the influences imposed by its environment (Lowe-Mc Connell, 1987;  
54  
55 306 Wootton, 1990). Over the years it has been able to maintain the same breeding cycle and this  
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58 307 study confirms the previous results obtained in the same area (Table 3). The difference  
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60 308 observed for the duration of spawning is probably the result of an interannual variability in the  
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309 environment that has a real impact on its reproductive cycle (Boëly, 1982; Ettahiri et al.,  
1 2003). Differences in the temporal location of reproductive periods between Senegal and  
2 310 other countries would be caused by different climatic conditions (Cury and Fontana, 1988).  
3 311 The reproductive pattern of *S. aurita* as described in Senegal has, therefore, not changed for  
4 312 more than 40 years ago and has followed the changes in its habitat in West Africa.  
5 313

11 The sizes at first sexual maturity in this study were larger than those previously  
12 314 measured in Senegal almost 40 years ago (Table 4). This difference in the same area could be  
13 315 explained by a strategy of modifying the reproduction traits over the years. On the other hand,  
14 316 smaller mature sizes in the Mediterranean (Gaamour et al., 2001; Tsikliras and Antonopoulou,  
15 317 2006; Mustać and Sinovčić, 2012), in the southern Atlantic (Fontana and Pianet, 1973; Ghéno  
16 318 and Fontana, 1981) and in the western Atlantic (Fréon et al., 1997) were related to  
17 319 environments poorer in nutritional elements and climatic conditions that were different from  
18 320 those in Senegal (Nieland, 1982; Lomiri et al., 2008). The minimum legal size (120 mm)  
19 321 authorized by the Senegalese fisheries code (CRODT, 2004) is much less than the size at first  
20 322 sexual maturity found by most studies (185-200 mm), including the present study (200-225  
21 323 mm). As a precautionary measure, this minimum legal size should be increased, based on the  
22 324 updated sizes at first maturity found in this study.  
23 325

24 326 The absolute fecundity estimated in our study was significantly higher at Hann than at  
25 327 Mbour and Joal. A higher condition factor would enable efficient transfer of energy to gonad  
26 328 development and a high *GSI* should result in more eggs being produced by females (Trippel,  
27 329 1998). This was the case in our study where the average female *GSI* in October for Hann (6%)  
28 330 was higher than the average female *GSI*s in February for Mbour (4.5%) and Joal (4%). The  
29 331 fecundity of *S. aurita* was estimated by several authors for various areas where the species is  
30 332 abundant. The results obtained in the present study were higher to those reported for the same  
31 333 area (Pham-Thuoc and Szypula, 1973), for the northeastern and in the eastern Mediterranean  
32 334

334 (Tsikliras and Antonopoulou, 2006; Mustać and Sinovčić, 2012), for the Venezuelan coast  
335 (Fréon and Mendoza, 2003), and for the Congolese coast (Fontana and Pianet, 1973). The  
336 relative fecundity observed in the present study (Hann:  $654 \pm 111 \text{ g}^{-1}$  eggs, Mbour:  $301 \pm 98$   
337  $\text{g}^{-1}$  eggs, Joal:  $293 \pm 109 \text{ g}^{-1}$  eggs) brackets that reported by Conand (1977) for Senegal (400  
338 eggs  $\text{g}^{-1}$ ), that reported by Fréon and Mendoza (2003) for Venezuela (295 to 665 with an  
339 average of 400 eggs  $\text{g}^{-1}$ ) and that reported by Tsikliras and Antonopoulou (2006) for the  
340 northeastern Mediterranean (242 to 681  $\text{g}^{-1}$  eggs with an average of  $445 \pm 98$  eggs  $\text{g}^{-1}$  for sizes  
341 between 164 and 228 mm). These different fecundity values indicated that the fertility of *S.*  
342 *aurita* has a high fertility but with year to year variations in the same area, depending on the  
343 weight and size of the mature females (Fontana and Pianet, 1973; C. Conand, 1977). An  
344 increase in size at first sexual maturity therefore allows *S. aurita* to maintain the same relative  
345 fecundity while spawning many more eggs in Senegal. This suggests that the fecundity traits  
346 of *S. aurita* have changed over the past few decades.

#### 4.4. Age and growth

347  
348 There are very few studies focusing on estimating the age of fish using calcified parts  
349 in West Africa, and almost none on sardinellas. The analysis of size structures (Petersen  
350 method) is more often used for growth estimation, but results are subject to considerable bias,  
351 mainly depending on the sampling strategy which is affected by the selectivity of the fishing  
352 gear. The high variability in individual growth and a long reproductive period can lead to  
353 overlap between cohorts and make it difficult to divide the fish into age classes (Pham-Thuoc  
354 and Szypula, 1973; Boëly et al., 1978; Baldé et al., 2019). Our results showed that otoliths can  
355 be used for accurate age estimation of round sardinella along the Senegalese coasts. The rapid  
356 early growth observed has also been previously reported for round sardinella in NWA (Boëly  
357 et al., 1982b), and also for a congeneric species, the oil sardine *S. longiceps*, on the southeast  
358 coast of India (Longhurst and Wooster, 1990), in northern Aegean (Tsikliras et al., 2005) and

1 359 in Congo (Ghéno and Fontana, 1981). The differences between the methodologies used to  
2 360 estimate the age may also explain some of the discrepancies in the mean growth rate.  
3  
4 361 Nevertheless, the asymptotic sizes were consistent with other results in the area (Table 4). It is  
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6  
7 362 true that the Senegalese waters seem very favorable for the growth of the species but the  
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9 363 biggest fish are found in Mauritanian (350 mm), even though the performance index was  
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11 364 higher in Senegal (Boëly et al., 1982b). Variation in environmental conditions, such as  
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13 365 temperature and food availability, between different areas, may affect the growth of *S. aurita*  
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15 366 (Bacha et al., 2016). It appears that the growth observed at Hann, Mbour and Joal was  
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17 367 representative of *S. aurita* growth in Senegalese coastal waters. There were, however, no very  
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19 368 large fish in the samples that we took. This could suggest a fully exploited stock or  
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21 369 environmental pressures, although this has not yet been confirmed.  
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## 29 370 5. Conclusion

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32 371 The conservation and management of aquatic resources along the Senegalese coast  
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34 372 requires a sound knowledge of the resources and up-to-date data on life history traits. The  
35  
36 373 management of the sardinella fisheries in Senegal often relies more on unverified hypotheses  
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38 374 than on data collected in the field. The present results highlight the need for better  
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40 375 management of these fisheries. Management measures should take into account the size at  
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42 376 first maturity to determine the fishing gear selectivity (suitable mesh size) as well as taking  
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44 377 account of the reproductive season. The current legal minimum legal size of the round  
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46 378 sardinella in Senegal and in the area should be increased from 120 to at least 200 mm, the  
47  
48 379 approximate size at first maturity being estimated at more than 200 mm. This would increase  
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50 380 the reproductive success. Life history traits such as the reproductive period and the growth  
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52 381 curves have remained stable, but variable, over several decades. The present study shows that  
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54 382 only real indication of the effects of exploitation is the small number of large size individuals  
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383 in the samples that we took. There is a general belief that this stock is currently overexploited  
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2 384 in Senegalese waters (Sow et al., 2010; FAO, 2017), and this study confirms that the stock of  
3  
4 385 round sardinella (*S. aurita*) is fully exploited in Senegal and management measures should  
5  
6  
7 386 still be taken (larger mesh sizes).  
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### 43 401 **Author contributions**

44  
45 402 Conceptualization: OS JP KD PN.; Data curation: OS MF.; Data analysis: OS JP.;  
46  
47 403 Methodology: OS.; Project administration: KD JP.; Resources: OS MF.; Software: OS JP.;  
48  
49 404 Validation: JP, MF.; Supervision: JP PN MF.; Writing original draft: OS.; reviewing: JP KD.;  
50  
51 405 All authors contributed critically to the drafts and gave final approval for publication.  
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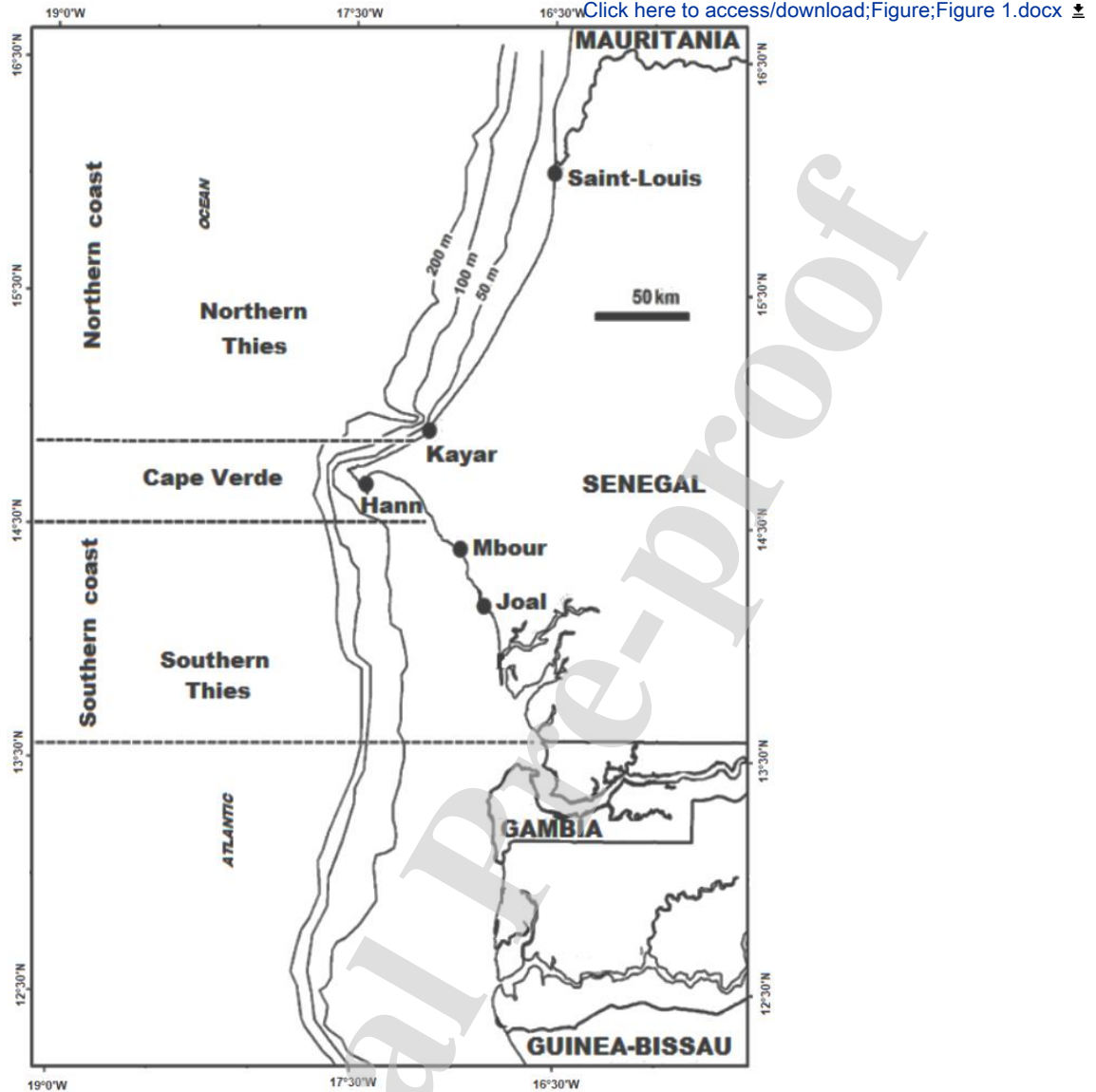
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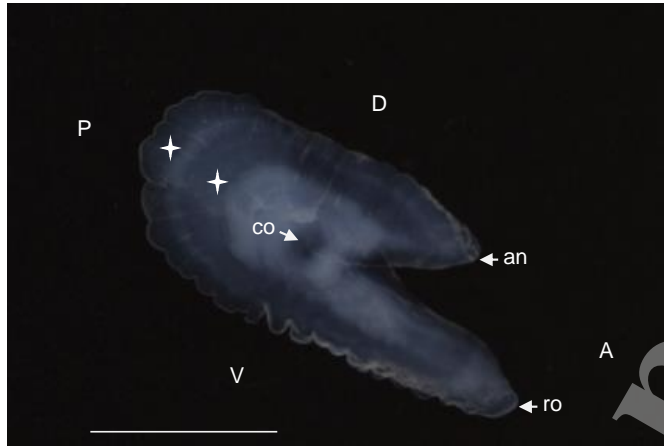
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Figure 1



**Fig. 1.** Sampling locations of *Sardinella aurita* in Senegal: Hann, Mbour and Joal for life history traits and Saint Louis, northern Thiès, Cape Verde and southern Thiès for fish landings.

Figure 2

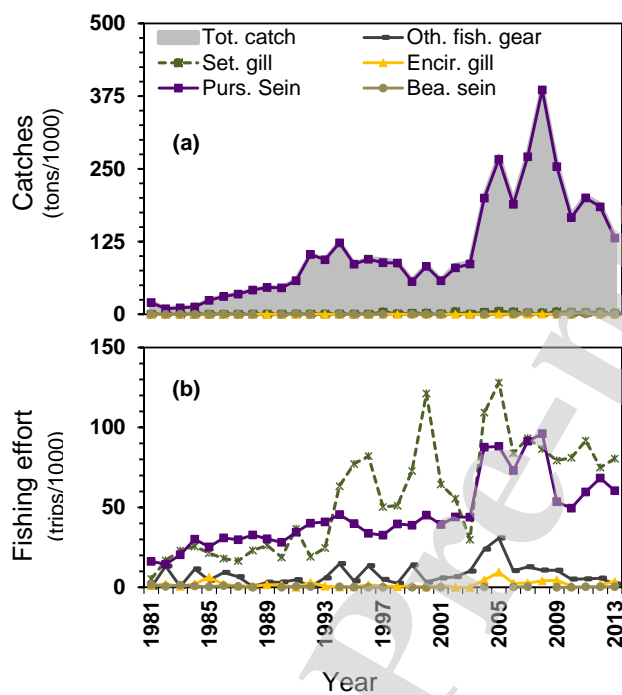
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**Fig. 2.** *Sardinella aurita* otolith viewed with a binocular microscope after immersion in 95% ethanol under reflected light against a dark background. The distal otolith face is shown. Two translucent marks (stars) are visible from the core, both along the rostrum and towards the posterior margin. Scale bar = 1.5 mm.

P = posterior; V = ventral; A = anterior; D = dorsal; co = core; an = antirostrum; ro = rostrum.

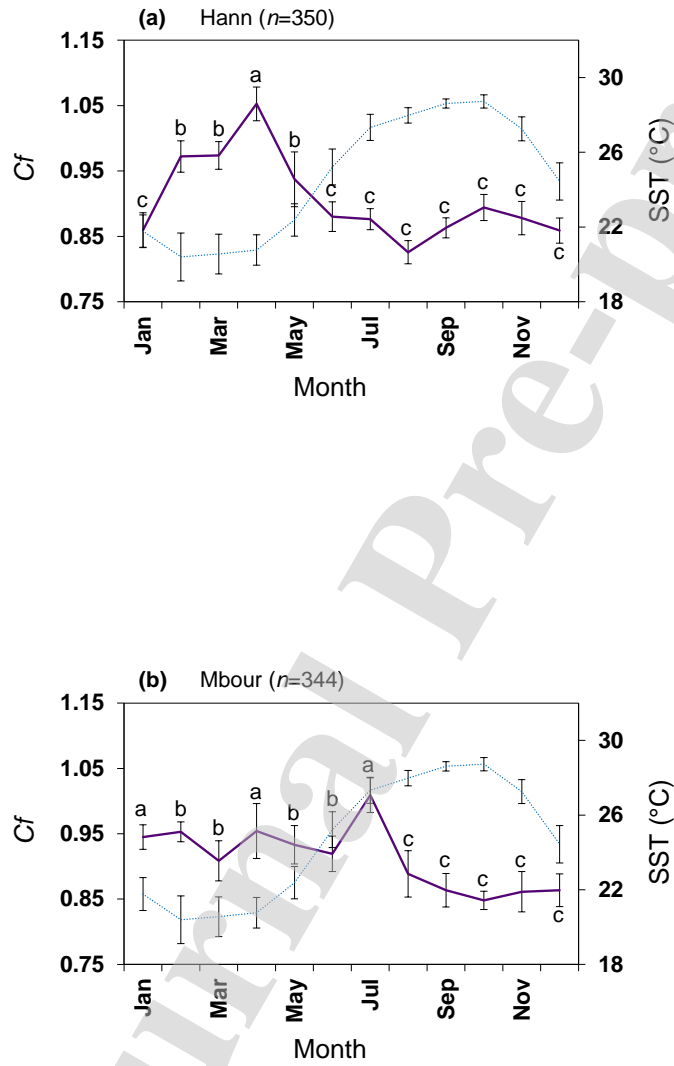
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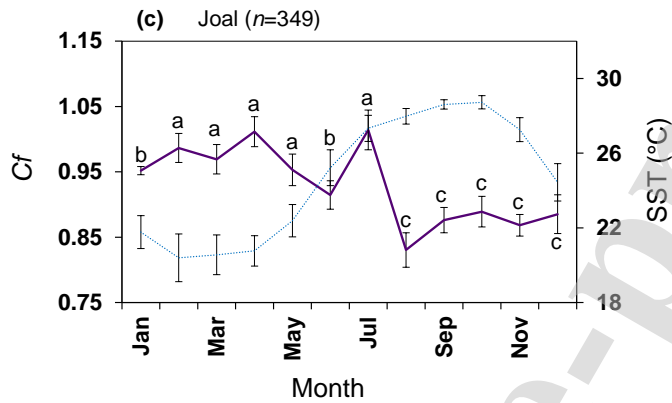
Figure 3

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**Fig. 3.** Annual catches (a) and fishing effort (b) for *Sardinella aurita* in Senegalese coastal waters between 1981 and 2013. Tot. catch = total catch; Set. gill = set gillnets; Purs. Sein = purse seines; Oth. fish. gear = other types of fishing gear; Encir. gill = encircling gillnets; Bea. sein = beach seines.

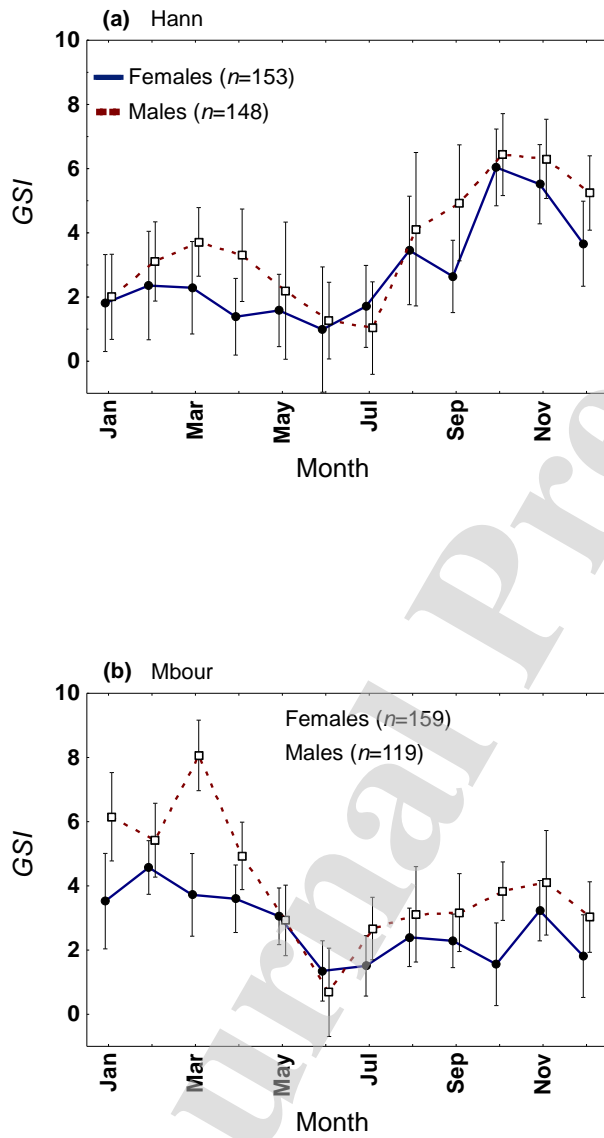
Figure 4

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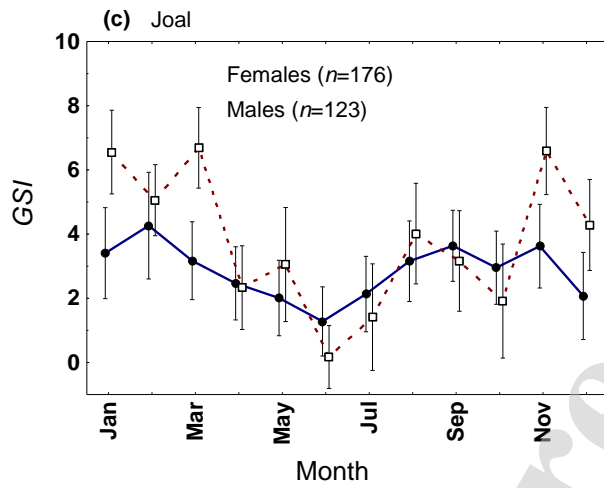
**Fig. 4.** Monthly sea surface temperature [(.....) mean SST $\pm$  SD] and condition factor of *Sardinella aurita* [(—) mean Cf $\pm$  SD] for Hann, Mbour and Joal locations. Same letters above means indicate that Cf values were statistically identical (Mann-Whitney test).

Figure 5

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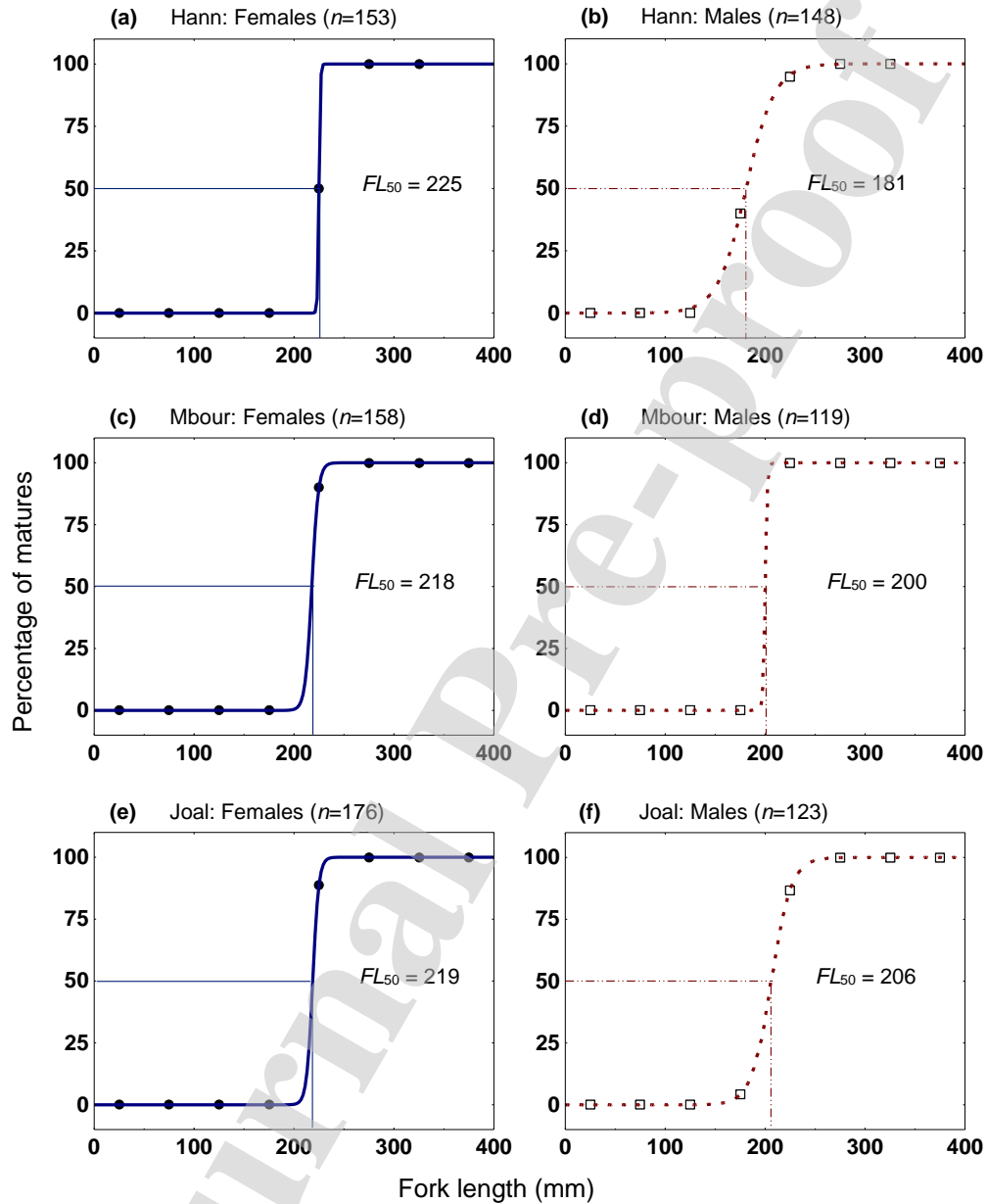


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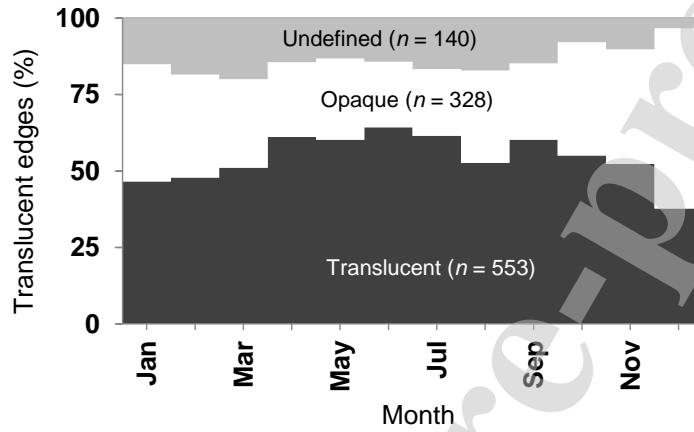
**Fig. 5.** Monthly gonado-somatic index of *Sardinella aurita* (mean GSI  $\pm$  SD) for Hann, Mbour and Joal locations.

Figure 6

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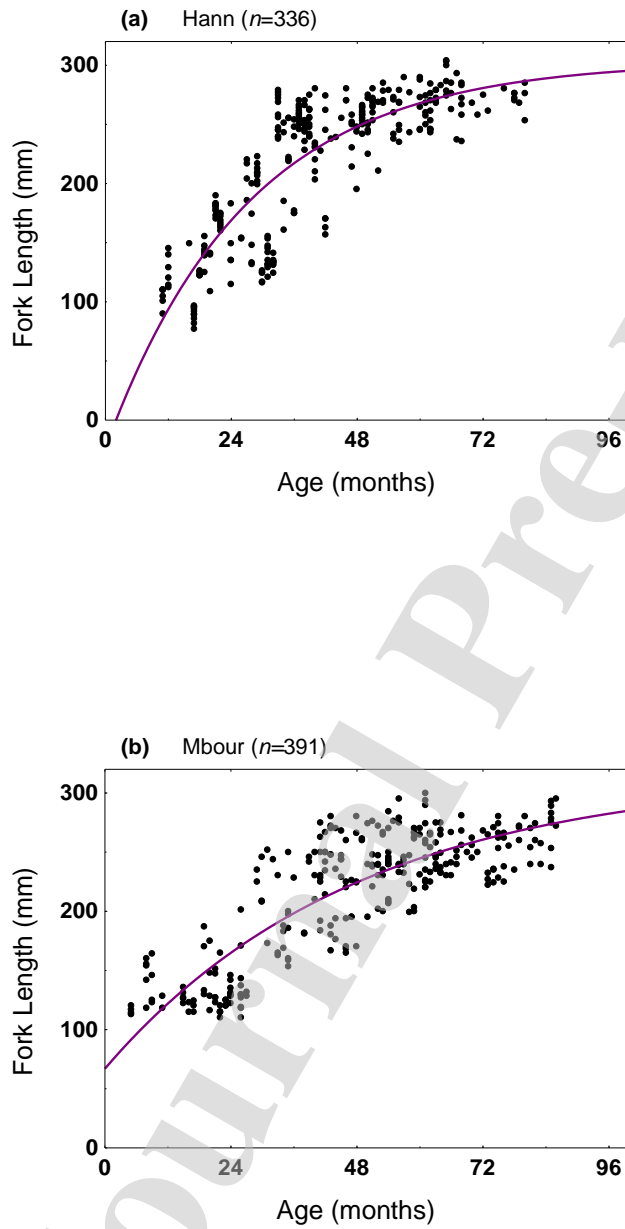
**Fig. 6.** Logistic functions for estimating the fork length at the first sexual maturity ( $FL_{50}$ ) of *Sardinella aurita* for Hann, Mbour and Joal locations.

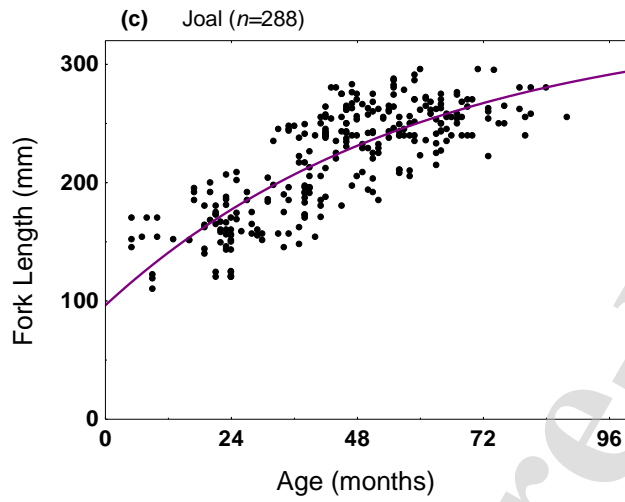
Figure 7

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**Fig. 7.** Monthly percentages of otolith translucent edges for *Sardinella aurita* (in dark grey). The opaque edge percentage is in white and the undefined edge percentage is in grey.

Figure 8

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**Fig. 8.** Von Bertalanffy growth functions of *Sardinella aurita* for Hann, Mbour and Joal locations.  $n$  = number of otoliths read for both sexes combined.

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Table 1

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**Table 1.** Fecundity parameters of *Sardinella aurita* for Hann, Mbour and Joal (A) and pairwise comparison of those parameters between the three sampling locations using parametric Student's *t* test (B). Min-Max = fecundity parameters range; SD = standard deviation;  $F_A$  = absolute fecundity;  $F_R$  = relative fecundity;  $D_{ov}$  = ovocyte diameter.

Significant differences between two locations are shown in bold with a significance level of 5% ( $P < 0.05$ ); *t* = Student *t* test; *p* = the probability of the test

(A)	Hann		Mbour		Joal	
Fecundity parameters	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)
$F_A$ (nb eggs)	111,390-253,340	176,315 (45,949)	50,118-212,544	101,036 (45,804)	37,758-143,307	80,784 (31,555)
$F_R$ (egg g <sup>-1</sup> )	503-815	654 (111)	118-512	301 (98)	175-532	293 (109)
$D_{ov}$ (mm)	0.62-0.70	0.66 (0.03)	0.59-0.68	0.63 (0.03)	0.54-0.70	0.63 (0.04)

(B)	Hann vs Mbour		Hann vs Joal		Mbour vs Joal	
Fecundity parameters	<i>t</i>	<i>p</i>	<i>t</i>	<i>p</i>	<i>t</i>	<i>p</i>
$F_A$ (nb eggs)	3.67	<b>0.00</b>	5.42	<b>0.00</b>	1.15	0.26
$F_R$ (egg g <sup>-1</sup> )	7.55	<b>0.00</b>	7.31	<b>0.00</b>	-0.16	0.87
$D_{ov}$ (mm)	2.04	0.06	2.10	0.05	0.46	0.65

Table 2

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**Table 2.** Growth parameters and performance index of *Sardinella aurita* for Hann, Mbour and Joal.  $LF_{\infty}$  = asymptotic fork length;  $K$  = growth coefficient;  $t_0$  = theoretical age at which the length is null;  $\Phi'$  = performance index;  $LF$  = fork length

Locations	$n$	$LF_{\infty}$	$K$	$t_0$	$\Phi'$	Range	
						$LF$ (mm)	Age (months)
Hann	336	304	0.04	2.02	3.53	77-307	11-80
Mbour	391	316	0.02	-11.44	3.32	110-300	5-86
Joal	288	340	0.02	-19.8	3.29	110-296	5-88

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Table 3

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Table 3. Reproductive periods of *Sardinella aurita* in various areas of its distribution. The reproductive period is presented by the black points.

Area	Reproductive periods												References
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
<i>Eastern Atlantic</i>													
Hann (Senegal)											•	•	Present study
Mbour (Senegal)	•	•	•	•									Present study
Joal (Senegal)	•	•	•	•					•	•	•	•	Present study
Senegal		•	•	•	•	•				•	•	•	(Cury and Fontana, 1988)
Senegal		•	•	•	•	•				•	•	•	(Boëly, 1982)
Senegal			•	•	•	•					•	•	(F. Conand, 1977)
Senegal		•	•	•	•	•					•	•	(Boëly et al., 1978)
Ghana offshore							•	•	•	•			(Quatey and Maravelias, 1999)
Gambia-Cap Blanc						•	•	•	•	•			(Boëly et al., 1978)
Congo					•	•	•	•	•	•			(Fontana and Pianet, 1973)
Sahara - Cape Verde peninsula					•	•	•	•	•	•	•		(Boëly and Fréon, 1979)
Sahara - Cape Verde peninsula					•	•	•	•	•	•	•		(Pham-Thuoc and Szypula, 1973)
Mauritania	•						•	•	•			•	(Chavance et al., 1991)
Mauritania						•	•	•	•				(Wagué and Mbodj, 2002)
Mauritania						•	•	•	•				(Ter hofstede et al., 2007)
<i>Western Atlantic</i>													
Venezuela	•	•	•									•	(Fréon et al., 1997)
Brazil	•											•	(Matsuura, 1996)
<i>Mediterranean</i>													
Northeast Mediterranean					•	•	•						(Tsikliras and Antonopoulou, 2006)
East Mediterranean						•	•	•					(Mustać and Sinovčić, 2012)
Middle Mediterranean							•	•	•				(Gaamour et al., 2001)
West Mediterranean							•	•	•				(Palomera and Sabatés, 1990)



Table 4

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**Table 4.** Age, sizes and performance index of *Sardinella aurita* in various areas of its distribution. NE = Northeast; leng. freq = length frequency;  $LF_{\infty}$  = asymptotic fork length; Max.  $LF$  = maximal fork length observed; Max. age = maximal age calculated by differ authors;  $\Phi'$  = performance index;  $LF_{50}$  = size at first sexual maturity; N/A = not available

Area	Methods	$LF_{\infty}$ (mm)	Max. $LF$ (mm)	Max. age (months)	$\Phi'$	$LF_{50}$ (mm)		References
						female	male	
<i>Eastern Atlantic</i>								
Hann (Senegal)	otolith	304	307	80	3.53	225	181	Present study
Mbour (Senegal)	otolith	316	300	86	3.32	218	200	Present study
Joal (Senegal)	otolith	340	296	88	3.29	219	206	Present study
Senegal	leng. freq. scale	306.3	321	72	3.98	200	N/A	(Boëly, 1982; Boëly et al., 1982b)
Senegal	scale	331.5	320	96	3.41	185	N/A	(F. Conand, 1977; Krzeptowski, 1981)
Mauritania	scale	343	350	84	3.51	219	226	(Pham-Thuoc and Szypula, 1973; Ter Hofstede and Dickey-Collas, 2006)
Ghana	N/A	N/A	N/A	N/A	N/A	171	167	(Quatey and Maravelias, 1999)
Congo	leng. freq. scale	260	280	90	3.83	160	N/A	(Ghéno and Fontana, 1981)
<i>Western Atlantic</i>								
Florida	otolith	220.1	190.5	48	3.28	N/A	N/A	(Grall, 1984)
Venezuela	leng. freq.	235			3.76		170	(Mendoza et al., 1994; Fréon et al., 1997)
Brazil	leng. Freq, otolith	243	220	48	3.43	N/A	N/A	(Cergole et al., 2002)
<i>Mediterranean</i>								
NE Mediterranean	leng. freq. scale	220	219	60	3.31	146	135	(Tsikliras et al., 2005; Tsikliras and Antonopoulou, 2006)
Algeria	leng. freq.	243	238	54	3.30	N/A	N/A	(Belouahem, 2010)
Tunisia	otolith	277	242	84	3.19	135	125	(Gaamour et al., 2001)
Egypt	leng. freq. scale	229	200	48	3.12	N/A	N/A	(Salem et al., 2010)
Adriatic sea	N/A	N/A	N/A	N/A	N/A	145	137	(Mustać and Sinovčić, 2012)

Highlights

- Condition factor of the round sardinella is a very good indicator
- Reproductive pattern has not changed for more than 40 years ago
- The reading of the otoliths gave a good estimate of the age and growth
- Growth was rapid and variable with longevity of 6-7 years
- Decline in landings could be related to the reduction in the annual number of trips

**Conflict of Interest**

This manuscript has not been published or simultaneously submitted for publication elsewhere. We have no conflicts of interest to disclose. This proposal of publication has been approved by all authors and tacitly by the responsible authorities where the work was carried out. All authors agree to the submission of this research and take full responsibility for its content.