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1 **Fish-length based indicators for improved management of the sardinella**  
2 **fisheries in Senegal**

3

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## 15 **ABSTRACT**

16 Fisheries management is difficult especially in developing countries where there are little or no data  
17 available for stock assessment. Here, a simple model based on the length-based Bayesian biomass  
18 (LBB) is applied to length frequencies collected on the two sardinella species (*Sardinella maderensis*  
19 and *S. aurita*) collected in Senegalese waters (2004 to 2014) to diagnose these stocks and to support  
20 the development of fishery management options that may improve the livelihoods of artisanal  
21 fishermen. Annual mean length of both species of sardinella showed a large variation during the  
22 decadal study period. It is assumed that such variations are due to environmental changes. According  
23 to our results, based on the current exploitation rate, both sardinella species are overexploited. To  
24 reverse these bad stock status, three management indicators were estimated for both sardinella: (i)  
25 length at first capture (Total Length (TL);  $L_c$  24 and 27 cm for *S. maderensis* and *S. aurita*,  
26 respectively); (ii) the length at maximum possible yield per recruit (TL;  $L_{opt}$  26 and 29 cm for *S.*  
27 *maderensis* and *S. aurita*, respectively); and (iii) the optimal length for the first capture (TL;  $L_{c,opt}$ ; 25  
28 and 28 cm for *S. maderensis* and *S. aurita*, respectively). According to Senegalese maritime fishing  
29 code, which sets the small pelagic fish size of the first capture  $\geq 18$  cm, we urge the Senegalese  
30 governments to press ahead with much needed reforms of the fishing code. We recommend capturing  
31 sardinella at the size  $L_{c,opt}$  to provide a natural safeguard against any recruitment failure related to  
32 environmental variability and allow individuals to grow and ensure the long-term survival of  
33 populations and thus sustainable fisheries. The results suggest that LBB model could be a tool to  
34 assess data-poor fisheries allowing the possibility to include in the analysis several years of length-  
35 frequency data with a minimum of prerequisites.

36 **Keywords:** Data poor fisheries; Fisheries management; Shared stocks; Small scale fisheries; Small  
37 pelagic fish; West Africa.

## 38 1. INTRODUCTION

39 For small-scale, data-poor fisheries where age data collection is often limited by lack of technical  
40 expertise and funds, length-frequency data is often the only form of information available for  
41 researchers and managers (Baldé et al., 2018). Length-frequency data, when available, can be used by  
42 researchers to inform management. Length is also an important index of the biomass (length-weight  
43 relationship), the biology (number of eggs produced according to the size of the body) and the trophic  
44 position of many fish species (*e.g.*, Hixon et al., 2014). The length of the organisms is thus a  
45 determining parameter in the ecological processes of the species. Due to the rapid availability of  
46 length data for many stocks, a number of length-based methods have been developed and applied to  
47 estimate biological parameters and to understand the dynamics of fish populations (Froese et al., 2018,  
48 2016; Mildenberger et al., 2017). Thus, it is possible to conduct simple size-based assessments of  
49 many stocks considered too poor in data to be evaluated (Froese et al., 2018). Several size-based  
50 techniques have been developed to estimate fish growth and mortality rates (*e.g.*, McQuinn et al.,  
51 1990; Pauly, 1983). Other length-based techniques using the population size structure to estimate  
52 stock status and assist managers have been implemented recently (*e.g.*, Froese et al., 2018; Hordyk et  
53 al., 2014; Thorson and Cope, 2015).

54 For example, the length-based empirical estimation method of spawning potential ratio (LB-SPR)  
55 model implemented by Hordyk et al. (2014), estimates the length selectivity and the  $F/M$  ratio, which  
56 are then used to calculate the Stock Reproductive Potential Ratio (SPR). The SPR is defined as the  
57 proportion of unexploited breeding potential, regardless of the level of fishing pressure retained  
58 (Walters and Martell, 2004). This equilibrium-based method, which assumes constant recruitment,  
59 cannot accommodate multimodal length composition, a situation known as the "Lee's phenomenon"  
60 (Lee, 1912). As a result, any estimate of  $F/M$  ratio, selectivity, and SPR may be unrealistic. To cope  
61 with this handicap, Hordyk et al. (2016) developed a new length structured model using the Growth-  
62 Type-Group approach (GTG). Indeed, this new model has the particularity, compared to LB-SPR, of  
63 using the life-time ratio  $M/K$ , as well as estimates of the size at first maturity ( $L_{50}$ ), the asymptotic  
64 length ( $L_{\infty}$ ) and the length composition, to estimate the potential spawning ratio with size-dependent

65 selectivity models (Hordyk et al., 2016). However, in the case where the selectivity is not age-  
66 dependent, the results of the model may be strongly biased. Another model, Length-based Integrated  
67 Mixed Effects (LIME), is used to study age-structured population dynamics (Rudd and Thorson,  
68 2017), while taking into account variable fishing mortality and recruitment over time, which makes it  
69 different from the two models mentioned above (LB-SPR and GTG). For the LIME model, the input  
70 parameters are data on the length composition of catches for a given year as well as information on the  
71 assumed life cycle, including the length-age relationship, an assumed natural mortality rate, and a  
72 length at 50% of maturity (Rudd and Thorson, 2017). However this model works well only for fish  
73 with a short life span. The higher the age of the fish, the greater the uncertainty becomes. Indeed, the  
74 increasing length makes cohorts unclear with age, making it difficult to track recruitment events  
75 without a much longer time series of length data (Rudd and Thorson, 2017). And like LB-SPR and  
76 GTG, LIME requires setting biological parameters and good knowledge of species biology to their  
77 true value for estimating unbiased reference points.

78 Thereby, a new model based solely on length frequencies called Length-based Bayesian biomass  
79 (LBB) seems to be an interesting option for estimating tropical and subtropical stocks poor in data  
80 (Froese et al., 2018). However, Hordyk et al. (2019) found that LBB model has some major problems  
81 such as the values of the  $M / K$  relationship that can change depending on the species exploited. As a  
82 result, a misinterpretation of values of this relationship can bias the results. Froese et al. (2019)  
83 indicates that these parameters can be taken into account by LBB model users and modified according  
84 to the available information. According to Froese et al. (2018), this model is a length-based Bayesian  
85 estimator that further reduces data requirements for preliminary stock assessments. The LBB model  
86 assumes that most tropical and subtropical species reach maximum size at maximum age. This implies  
87 that somatic growth and natural mortality of adults are aligned so that they can be expressed in a  
88 constant ratio (Froese et al., 2018). In tropical areas such as West Africa where species growth is rapid  
89 (*e.g.*, Ba et al., 2016; Baldé et al., 2019) and mortality is growth dependent ( $Z/K$ ) (Froese et al., 2018),  
90 the LBB model appears to be more appropriate. This model was largely developed by Froese et al.  
91 (2018) and may be useful to provide management options for stocks with limited catch data. The LBB

92 allows a simple analysis of size frequency data to obtain the length at first capture that would  
93 maximize catch and biomass for the given fishing effort, and provides an estimation of a proxy for the  
94 relative biomass capable of producing maximum sustainable yields. The model only requires length  
95 frequency data, length at first maturity ( $L_{50}$ ) and life cycle parameters as inputs. LBB model estimates  
96 percentage of mature individuals, relative natural mortality ( $M$ ) and relative fishing mortality ( $F$ ) as  
97 means over the age range represented in the length-frequency sample (Froese et al., 2018).

98 This study demonstrates the applicability of the LBB model, for the first time in West Africa, on  
99 small-scale data-poor fisheries, and illustrates the results of the assessment. In this work we assess the  
100 stock status of two commercially important species, which account for 75% of total landings of small  
101 pelagic species in 2015 from Senegalese waters (Thiao et al., 2016). The approach applied is based on  
102 two sets of stock status indicators that are well suited to data-poor fisheries. Indeed, they require only  
103 data of length frequency representative of the *Sardinella maderensis* and *Sardinella aurita* fisheries  
104 over 11 years, collected in Senegalese waters, and other external life cycle parameters generally  
105 available in the literature. It is hoped that these results could help in assessing many stocks currently  
106 considered too data poor to be evaluated, especially in developing countries.

## 107        **2. MATERIAL AND METHODS**

### 108        **2.1. Study area**

109        The Senegalese coast is divided between the Northern and the Southern part (Petite Côte and  
110        Casamance). The Northern part (Figure 1) extends from Saint-Louis (16 ° 04 N) north to the tip of the  
111        Almadies (14 ° 36 N). It is characterized by the presence of strong swells, a succession of dunes and  
112        coastlines. This area is home to cold, salty waters as early as October and covering the entire  
113        continental shelf by January (Faye et al., 2015). There is the presence of a large canyon in Kayar (15 °  
114        00 N). The Northern part concentrates very important fishing centers such as Saint-Louis and Kayar in  
115        relation with the present ecological conditions and a strong presence of the traditional fishing  
116        communities.

117        The Petite Côte (14 ° 36 N at 13 ° 36 N, Figure 1) has a great geomorphological and biodiversity  
118        richness: cords and sand arrows, cliffs, bays, lagoons and mangrove estuaries (Saloum estuary,  
119        lagoon-estuarine system of Somone (Baldé et al., 2018). This area is home of a seasonal upwelling cell  
120        that affects ambient temperature fluctuations in the area. Due to the topography of the continental  
121        shelf, the trade winds in the north induce a strong upwelling in winter (November to December)  
122        (Ndoye et al., 2017, 2014). Combined with sunlight, rich groundwater nutrients promote  
123        phytoplankton production (Auger et al., 2016). This is at the base of the food chain in all oceanic  
124        upwelling ecosystems and serves as a food source for the upper trophic levels where small pelagic fish  
125        are distributed.

126        The Casamance (13 ° 04 N and 12 ° 20 N, Figure 1) is located between the borders of The Gambia and  
127        Guinea Bissau. The continental shelf reaches its maximum width, at nearly 54 miles and the rocky  
128        bottoms are located offshore, mainly on the edge of the plateau. Its estuary is in fact an estuary which  
129        runs for 250 km inside the continent (Sakho, 2011). It receives inputs of fresh water only during the  
130        rainy season which lasts only 5 months, from June to October. The climate is mainly characterized by  
131        the alternation of a hot wet season from around July to October and a cold dry season from around  
132        November to June. During the dry season, the many small streams that form the Casamance River are

133 often dry. Declining rainfall in the Casamance River Basin and increased temperature have resulted in  
134 a runoff deficit and saline intrusion (Thiam and Singh, 2002).

## 135 **2.2. Study species**

136 In Senegal, two species of coastal pelagic fish appear to dominate the epipelagic fish biomass  
137 sequentially: *S. maderensis* and *S. aurita* (Diankha et al., 2018; Thiaw et al., 2017). *S. maderensis* is a  
138 species with tropical affinity tolerating temperature ranges from 20 to 23 ° C (Marchal, 1991) and it is  
139 found from the southern Mediterranean to Angola (Whitehead, 1985). According to Ben-Tuvia (1960),  
140 depending on the region, it can withstand temperatures ranging from 15 ° C to 25 ° C (in Algeria) and  
141 salinities ranging from 20 ‰ at the level of estuary of large rivers (Niger, Congo, Nile) to 40 ‰ in the  
142 eastern Mediterranean. It spawns throughout the year in Senegal. The first breeding season runs from  
143 April to October. A second breeding season, with continuous reproduction (more intense than during  
144 the first period), occurs from January to the end of February (Ba et al., 2016). In Senegal, catches of *S.*  
145 *maderensis* increased significantly during the period from 1981 to 2003, reaching a peak of more than  
146 100,000 tons per year, but subsequently declined to below 60,000 tons per year in 2010 (Figure 2).

147 The species *S. aurita*, lives in the tropical and subtropical regions of the eastern Atlantic and is found  
148 in large concentrations along the West coast of Africa in three main areas (Roy et al., 1989): between  
149 southern Morocco (Western Sahara) and Guinea (26 ° -10 ° N), between Côte d'Ivoire and Ghana (7 °  
150 - 5 ° N) and and further south between Gabon and southern Angola (0 ° -18 ° S) (Froese and Pauly,  
151 2016). *S. aurita* is also present in the western Atlantic Ocean, from Cape Cod (United States) to  
152 Argentina, including the West Indies and the Gulf of Mexico (Felder, 2009). It also lives in the  
153 Mediterranean Sea (Boltachev and Karpova, 2014). In all regions, the species preferentially inhabits  
154 continental shelves where it prefers saline waters (between 34 ‰ and 36 ‰), and warm sea  
155 temperatures (between 17° C and 30 °C; Boëly, 1979). The first reproductive period occurred from  
156 February to May off Senegal. A second reproductive period, with continuous spawning (more intense  
157 than during the first period), occurred from October to the end of December (Baldé et al., 2019).  
158 Catches of *S. aurita* in Senegal showed an increase between 1966-1998 and 2005-2011 and a slight  
159 decrease between 1999-2004 (on average 100 086 tons of catches; Figure 2).

### 160        **2.3. Biological data**

161        Data on the growth of *S. maderensis* and *S. aurita* were obtained from fish landed from January 2004  
162        to December 2014 in the seven main artisanal fishing ports along the Senegalese coast (Table 1;  
163        Figure 1). Three landing sites (Kayar, Saint-Louis and Yoff) are located in the Northern part. The  
164        other landing sites (Hann, Mbour, Joal and Kafountine) are located along the Southern part (Petite  
165        Côte and Casamance). Length data were collected at random approximately 5 days per week. This  
166        study used only specimens captured with purse seiners in order to have the same selectivity for fishing  
167        gear in monthly statistics to allow the comparisons of size distribution. A total of 143,984 and 193,283  
168        fish samples were recorded along the Senegalese coast during the surveys (2004-2014) for *S.*  
169        *maderensis* and *S. aurita*, respectively (see supplementary material). Total length (TL in cm) of fish  
170        was measured to the nearest cm, to calculate size-frequency distributions and to estimate growth  
171        parameters.

### 172        **2.4. Environmental data**

173        We used local environmental indices as the Coastal Upwelling Index (CUI) and coastal sea surface  
174        temperature (SST) for the period from 2004 to 2014 to analyse the effect of the environmental  
175        conditions on inter-annual variability of sardinella mean length in Senegalese waters. The  
176        methodology used to calculate CUI ( $\text{m}^3 \text{s}^{-1} \text{m}^{-1}$ ) and SST ( $^{\circ}\text{C}$ ) has been widely described by Baldé et  
177        al. (2019). The SST data (averaged on a monthly basis) were obtained from advanced, very-high-  
178        resolution radiometer (AVHRR) satellite images (5 km resolution) where upwelling-induced SST  
179        anomalies are generally maximal (Thiaw et al., 2017). The CUI was deduced from wind speed data  
180        obtained from the U.S. NOAA Environmental Research Division website (ERD, Upwelling and  
181        Environmental Index Products, <http://www.pfeg.noaa.gov>; Upwelling and Environmental Index  
182        Products, last visited: 20/11/2017).

## 2.5. Simulation model

The simulation carried out in this work involves the empirical estimation of the stock status ( $Z/K$ ,  $E$ ) as well as catch control indicators ( $L_c$ ,  $L_{opt}$  and  $L_{c\_opt}$ ; Table 2) in order to adjust the fishing effort to sustainable stock exploitation.

The von Bertalanffy (1938) growth parameters [coefficient of growth rate ( $K$ ), asymptotic length ( $L_\infty$ ), time “ $t$ ” when the fish length is zero ( $t_0$ )] of *S. maderensis* et *S. aurita* were estimated from monthly length-frequency data (2004-2014) using the ‘TropFishR’ (Tropical Fisheries Analysis with R) package (Mildenberger et al., 2017). Length-based Bayesian biomass (LBB) model of Froese et al. (2018) included in ‘TropFishR’ package was also used in this study. Allometric parameters ( $a$  and  $b$ ), length-at-maturity ( $L_{50}$ ) data and life cycle parameters for LBB model were obtained from Ba et al. (2016).

Calculations were computed using in R software and MS-Excel, and alternatively used the following basic equations. The meanings of the variables used in the formulas have been added in Table 3.

All fork length (FL in cm) measurements were converted to total length (TL) according to the relationship (Sylla et al. 2016):

$$FL = 1.08264 + 0.08066 TL \quad \text{Eq. 1}$$

Where

$$TL = (FL - 1.08264)/0.08066 \quad \text{Eq. 2}$$

The weight growth equation is obtained by combining the linear growth equation and the length-weight relationship:

$$W_t = W_\infty (1 - e^{-K(t-t_0)})^b \quad \text{Eq. 3}$$

Where  $W_t$  is the body weight at age  $t$ ,  $W_\infty$  is the asymptotic body weight,  $K$  is the coefficient of growth rate,  $t_0$  is the time “ $t$ ” when the fish length is zero and  $W_\infty = a * L_\infty^b$  with  $a$  and  $b$  are the parameters of the length-weight relationship. The parameters of the length-weight ratio used are derived from Ba et al. (2016).

208 The corresponding age at maximum growth ( $t_{max}$ ) rate is:

$$209 \quad t_{max} = \frac{\ln(3)}{K} + t_0 \quad \text{Eq. 4}$$

210 The body weight,  $W_{opt}$ , where unexploited cohort biomass reaches a maximum is given by Holt (1958)  
211 as:

$$212 \quad W_{opt} = W_{\infty} \left( \frac{K}{K + \frac{M}{3}} \right) \quad \text{Eq. 5}$$

213 The length,  $L_{opt}$ , corresponding to  $W_{opt}$  is given by Beverton (1992) as:

$$214 \quad L_{opt} = L_{\infty} \frac{3}{3 + \frac{M}{K}} \quad \text{Eq. 6}$$

215 The age at the peak of unexploited cohort biomass  $t_{opt}$  is given by:

$$216 \quad t_{opt} = \frac{\ln\left(\frac{3+M}{M}\right)}{K} + t_0 \quad \text{Eq. 7}$$

217 Starting fishing at  $L_{c\_opt}$  results in a mean length of  $L_{opt}$  for the catch and the exploits part of the  
218 population (Froese et al., 2016):

$$219 \quad L_{c\_opt} = L_{\infty} \frac{2+3F/M}{(1+F/M)(3+M/K)} \quad \text{Eq. 8}$$

220 The age  $t_{c\_opt}$  corresponding to  $L_{c\_opt}$  is obtained by:

$$221 \quad t_{c\_opt} = \frac{\ln\left(\frac{(Z)(3K+M)}{M(Z+K)}\right)}{K} + t_0 \quad \text{Eq. 9}$$

222 Total mortality ( $Z$ ) can be measured by:

$$223 \quad Z = F + M \quad \text{Eq. 10}$$

224 The exploitation rate ( $E$ ) was estimated using the formula:

$$225 \quad E = \frac{F}{Z} \quad \text{Eq. 11}$$

226 From the basic equations presented above, an index of yield per recruit expressed as a function of the  
227 length at first capture  $L_c$  is given by Beverton and Holt (1966) as:

228 
$$Y'/R = \frac{F/M}{1+F/M} (1 - L_C/L_\infty)^{M/K} \left( 1 - \frac{3(1-L_C/L_\infty)}{1+\frac{1}{M/K(1+F/M)}} + \frac{3(1-L_C/L_\infty)}{1+\frac{2}{M/K(1+F/M)}} - \frac{(1-L_C/L_\infty)^3}{1+\frac{3}{M/K(1+F/M)}} \right) \quad \text{Eq. 12}$$

229 Yield per recruit ( $Y/R$ ) curves were calculated using the Beverton-Holt yield per recruit model  
 230 (Beverton and Holt, 1957) :

231 
$$Y/R = F e^{-M(t_c-t_r)} W_\infty \sum_{n=0}^3 \frac{U_n e^{-nK(t_c-t_0)}}{F+M+nK} \quad \text{Eq. 13}$$

232 With  $t_r$  is the mean age (years) at recruitment to the fishing area,  $t_c$  is the mean age at first capture,  $U_n$   
 233 is the summation parameter ( $U_0=1, U_1=-3, U_2=3, U_3=-1$ ) and  $F$  is the fishing mortality coefficient.

234 Lastly biomass-per recruit ( $B/R$ ) curves was calculated using the following equation derived by  
 235 Beverton and Holt (1957):

236 
$$B/R = e^{-M(t_c-t_r)} W_\infty \sum_{n=0}^3 \frac{U_n e^{-nK(t_c-t_0)}}{Z+nK} \quad \text{Eq. 14}$$

237 We have calculated  $Y/R$  and  $B/R$  for a range of  $F$ -values, which produced a  $Y/R$  and  $B/R$  curve as a  
 238 function of  $F$  (Eskandari et al., 2013; Pitcher, 1999). The yield isopleths diagram of *S. maderensis* and  
 239 *S. aurita* was used to assess the impact on yield created by changes of exploitation rate  $E$  and the ratio  
 240 of length at first capture to asymptotic length ( $L_c / L_\infty$ ) in relation to changes in mesh size (Ama-Abasi  
 241 et al., 2004; Pauly and Soriano, 1986).

## 242 **2.6. Statistical analysis**

243 Statistical analyses were performed using the “stats”, “Hmisc” R packages (Harrell Jr, 2017;  
 244 McDonald, 2009) in RStudio 1.1.463 (Team, 2015), with a significance level of  $\alpha < 0.05$ . Annual  
 245 mean length of both sardinella were analysed using a one-way analysis of variance (ANOVA),  
 246 followed by a post-hoc Kruskal-Wallis test (Sokal and Rohlf, 1995). The Pearson test was used to  
 247 study the correlation between the annual mean length of each sardinella with the mean annual of each  
 248 environmental parameter, SST and CUI (Zar, 2014).

## 249 3. RESULTS

### 250 3.1. Annual variability of mean length of both sardinella related to 251 environmental parameters

252 The mean annual length of both species of sardinella remained fairly stable over the 11-years of the  
253 study period (Anova; F-value = 39.04,  $df = 1$ ,  $p$ -value < 0.05 for *S. maderensis* and F-value = 5.873,  $df$   
254 = 1,  $p$ -value < 0.05 for *S. aurita*) (Figure 3). The annual variation of the mean length during the study  
255 period showed two peaks of mean length for *S. maderensis*, one in 2007 (TL mean: 27 cm) and the  
256 other in 2014 (TL mean: 29 cm) whereas for *S. aurita* peaks are observed in 2008 (TL mean: 31cm)  
257 and 2010 (TL mean: 31 cm) (Figure 3). The mean annual length in 2014 was significantly higher than  
258 the other years of the study period (2004-2014) for *S. maderensis* (Kruskal-Wallis test,  $X^2 = 30178$ ,  $df$   
259 = 10,  $p$  value <0.001). While for *S. aurita*, the mean annual length in 2008 was higher than the other  
260 years of the study period (Kruskal-Wallis test,  $X^2 = 33275$ ,  $df = 10$ ,  $p$  value <0.001). Over the period  
261 2004-2014, the SST and CUI varied inter-annually. Mean SST increased in 2005, 2008 and 2010, but  
262 decreased in 2009 (Figure 3). CUI showed a quick and considerable increase in 2004 and 2009 (Figure  
263 3). No correlation was found between the annual mean length of each species and environmental  
264 parameters (Table 2).

### 265 3.2. Fishing mortality and exploitation rate for both sardinella

266 The mortality estimated (on samples 2004-2014) was  $Z = 2.3$  and  $2.4$  with  $F = 1.8$  and  $1.7$  and  $M = 0.5$   
267 and  $0.7$  for *S. maderensis* and *S. aurita*, respectively (Table 3). The  $F/M$  ratio was higher for *S. aurita*  
268 ( $3.6$ ) than for *S. maderensis* ( $2.4$ ). Using a LBB model,  $Z/K$  was estimated to be  $2.2$  and  $2.3$  for *S.*  
269 *maderensis* and *S. aurita*, respectively (Figure 4). For *S. maderensis* and *S. aurita*, the current rates of  
270 exploitation ( $E$ ) in Senegal waters were  $0.8$  and  $0.7$ , respectively. The yield contour predicts the  
271 response of the yield-per-recruit to changes in  $L_c$  and rate of exploitation  $E$ ;  $L_c / L_\infty = 0.7$  and  $0.8$  for *S.*  
272 *maderensis* and *S. aurita*, respectively.

### 273 3.3. Length-based indicators of fishing sustainability for both sardinella

274 The von Bertalanffy equations fit well with the observed data ( $R^2 \geq 0.90$  in all cases except in 2004  
275 and  $R^2 = 0.70$  for *S. maderensis* and *S. aurita*, respectively). Asymptotic length ( $L_\infty$ ) for the entire

276 period was 37.5 cm (TL) for both sardinella while  $L_c$  was 24.5 and 27.5 cm (TL) for *S. maderensis* and  
277 *S. aurita*, respectively (Figure 4). Our growth studies, indicate that growth of *S. aurita* and *S.*  
278 *maderensis* ( $K = 1.01$  and  $1.02$ , respectively) in Senegal is fast. The likelihood ratio test indicated that  
279 there was no difference between the  $K$  and  $L_\infty$  values of both sardinella species, which implies that  
280 they follow the same pattern of growth. When  $L_{50}$  were 20.3 cm for both sardinella species, 95 and  
281 92% mature individuals are observed for the entire study period for *S. maderensis* and *S. aurita*,  
282 respectively.

283 The biomasses of unexploited cohorts of *S. maderensis* and *S. aurita* were highest ( $L_{opt}$ ) at 26 and 29  
284 cm (TL) at an age of 1.9 and 1.3 years ( $t_{opt}$ ), respectively (Table 3). Optimal lengths at first capture  
285 ( $L_{c\_opt}$ ) were 25 and 28 cm (TL) for *S. maderensis* and *S. aurita* respectively (Table 3). The index of  
286 yield per recruit ( $Y'/R$ ) was estimated to be 0.2 for both sardinella (Table 3).

287 Changes of  $Y/R$  and  $B/R$  for *S. maderensis* and *S. aurita* according to various values of  $F$  and  $t_c$  are  
288 given in Figure 5. For *S. maderensis*, when  $M = 0.5$ ,  $Y/R$  (564 kg; Figure 5a) and  $B/R$  (2,862 kg; Figure  
289 5b) reach its maximum when  $t_c = 2.5$  year<sup>-1</sup>. While *S. aurita*,  $Y/R$  reached its maximum value (426 kg)  
290 after two to three years ( $t_c$ ) when  $M$  was 0.7 (Figure 5a) and  $B/R$  decreased rapidly as  $F$  increased.  
291 Maximum  $B/R$  occurred at  $t_c < 2.5$  years<sup>-1</sup> (1,387 kg; Figure 5b) for *S. aurita*.

## 4. DISCUSSION

The data for this work have significant disadvantages to consider. Senegalese sardinella cannot be isolated from sardinella caught in neighboring countries and any exploitation outside Senegal's maritime borders has a significant impact on production in Senegalese waters. Interpretation of the growth of both sardinella will depend on the season in which the samples are obtained and seasonal differences in growth have been reported (Thiaw et al., 2017). In migratory species such as sardinella, the input data in growth studies can often be biased, *i.e.*, some elements may be missing because the whole cohort may not be present in the area where the samples are taken. As a result, management guidelines and controls must be simple, but also robust protecting against uncertainties, as well as being proportionate to the information available (Pilling et al. 2009).

### 4.1. Growth variability of both sardinella

As fish growth is variable, a same species may have different growth patterns according to its environment (*e.g.*, Baldé et al., 2019). Indeed, during the study period (2004-2014), interannual variability was detected between the length distributions of both sardinella in Senegalese waters. These difference may be partly determined by the temporal difference (during the spawning period) when larvae hatch (Tiedemann and Brehmer, 2017), food availability (Thiaw et al., 2017) and environmental conditions (Diankha et al., 2018). Our results showed that the annual mean length of the two species of sardinella followed the CUI pattern (Figure 3). In the study area, primary production is, to a large extent, determined by upwelling processes (Auger et al., 2016) during the winter period (dry season), which can have a major effect on juvenile growth. During their migration, adults are subject to variable environmental conditions, which affect their growth and spawning potential (Tiedemann et al., 2017). The coincidence of the annual mean length peaks of the two round sardinellas with the lowest temperatures (Figure 3), could suggest that temperature is also an important factor in the control of sardinella growth in the study area. Another clupeid species the Pacific herring (*Clupea harengus pallasii*), had optimal juvenile growth with SST between 12 ° and 13 ° C (Haist and Stocker, 1985). Another cause of variability in sardinella growth rate could be the effect of abundance of cohort size (Thiaw et al., 2017) and recruitment. Diankha et al. (2018) showed that the key

319 environmental variables influencing the recruitment success are different for both studied species: the  
320 Coastal Upwelling Index and the SST for *S. aurita* and *S. maderensis*, respectively. Thus, we assume  
321 that the environmental variability can also have a significant impact on both sardinella species growth  
322 variability.

#### 323 **4.2. Diagnosis of sardinella fisheries**

324 The level of exploitation could be due to the increasing demand for sardinella for human consumption  
325 (*e.g.*, fresh, processed by hand and more recently in fishmeal), the increasing fishing effort of the  
326 Mauritanian-Senegalese artisanal fleets and the European Union (Baldé, 2019; Stilwell, 2008). For  
327 example, in Mauritania, the increase in fishing effort is linked to the expansion of the fish flour  
328 industry in Nouadhibou and Nouakchott (FAO, 2016). Indeed, landings of *S. aurita* to flour mills  
329 increased from 30% in 2012 to 45% in 2013 and to 62% in 2014 (FAO, 2016). The number of flour  
330 companies in operation has increased from 18 factories in 2012 to 22 in 2013 (FAO, 2016). The same  
331 scenario is noted in Senegal where production in Saint-Louis and along the Petite Côte (Mbour and  
332 Joal) is still stimulated by the existence of the sub-regional market and the establishment of fishmeal  
333 production plants (FAO, 2016). It is also worth reporting that catches off the Sahara bank have  
334 increased. Indeed, with climate change, there is an increased presence of *S. aurita* towards Cape Blanc  
335 in Morocco (Sarré, 2017). Thus, more sardinella were caught in Morocco between 2005 and 2014  
336 (Sarré, 2017). This can explain the significant decrease in *S. aurita* abundance in Senegal during this  
337 period (Thiaw et al., 2017), accentuated by a lack of sub-regional collaboration in their fisheries  
338 management (Nguyen et al., 2018). Indeed, the decline in industrial catches has been partially offset  
339 by an increase in landings by the fishing fleets of coastal states with a predominantly artisanal role  
340 (see Thiaw et al., 2017). This is also reflected in the decrease in fishing effort between 2004 and 2014  
341 in Senegalese waters (Figure 6) on both species.

342 The *F/M* ratio is high for *S. maderensis* ( $F/M = 3.6$ ) and *S. aurita* ( $F/M = 2.4$ ). This comes from the  
343 change of fishing techniques and the motorization of the Senegalese canoes in recent years. In fact, the  
344 Senegalese canoe fleets are by far the most important in the West African region (including Nigeria  
345 and Ghana). In 2005, the number of fishing units was estimated to 13, 900 while the last census in

346 2015 reported 18,284 fishing units, including more than 90% motorized canoes (Sow et al., 2016). The  
347 dynamism of the artisanal fisheries resides in its capacity to adapt permanently to the changes of the  
348 context of the activity. This adaptive capacity depends on the qualitative and quantitative of the  
349 resource availability, economic context with reference to the possibilities of flow of the products and  
350 the levels of market remuneration (Binet et al., 2012). The strong reactivity of the Senegalese artisanal  
351 fishermen is linked, among others, to their good knowledge of the behavior of the resources but also  
352 their great organizational capacities to deal with changing institutional environment and appropriation  
353 of new techniques to exploit new resources (Binet et al., 2012). Given the level of exploitation of these  
354 species and the development and modernization of small-scale fisheries, indicators based on length-  
355 frequencies should help sustainable management at a critical time for these fisheries.

### 356 **4.3. Indicators for sustainable management**

357 One of the objectives of fisheries management is to minimize the impact of fishing on the size and age  
358 structure of exploited populations (Froese et al., 2016). Indeed, fishing with no size limit further  
359 reduces biomass, especially if higher values of  $M$  and hence of  $F$  are applied to pre-recruits (Froese et  
360 al., 2015). In Senegal, according to the 2015 Fishing code, the mesh size allowed for sardinella  
361 fisheries is restricted between 40 and 60 mm that represents a fish size  $TL \geq 18.0$  cm. Nevertheless,  
362 the average sizes of individuals caught in both sardinella species are smaller than the  $L_{50}$  of 20.3 cm  
363 (TL) (Ba et al., 2016). In the long-term, this fact could prevent the sustainability of sardinella stocks  
364 because it does not allow them to renew properly. Indeed, sardinella species show patterns of spatial  
365 and temporal distribution by size group (Ba et al., 2016; Baldé et al., 2019). Indicators based on  
366 length- frequencies can be used to establish management measures for fisheries (Froese, 2004; Froese  
367 et al., 2016). The  $L_c$  found in our study is higher than the  $L_c$  indicated by the Senegalese fishing code  
368 ( $TL \geq 18.0$  cm) and also the  $L_{50}$  (20.3 cm) for both sardinella species found by Ba et al. (2016).  
369 Fishing at  $L_c$  (24.5 and 27.5 cm for *S. maderensis* and *S. aurita*, respectively) would allow all fish to  
370 reproduce at least once before being caught. This will result in rebuilding and maintaining  
371 reproductive stocks in good health. However, such a tactic is only possible if the recruitment is  
372 successful each year. According to Diankha et al. (2018), the recruitment of *S. maderensis* and *S.*

373 *aurita* in Senegal is subject to variation depending on the sea surface temperature and the coastal  
374 upwelling index, respectively. As a result, the environment will have to be taken into account in this  
375 sustainable fishery hypothesis. The second indicator  $L_{opt}$  (26 and 29 cm for *S. maderensis* and *S.*  
376 *aurita*, respectively) is the length where maximum yield can be obtained. This focus on large  
377 specimens is based on the growing evidence that older fish play several important roles in the long-  
378 term survival of a population (*e.g.*, egg production; Baldé et al., 2019). This size ( $L_{opt}$ ) is greater than  
379  $L_c$  found in our study, therefore greater than  $L_c$  indicated by the Senegalese fishing code and the  $L_{50}$  of  
380 both sardinella. However, the realities of Senegalese fisheries must be taken into account. In fact, to  
381 cope with the scarcity of resources, Senegalese fishermen are increasingly using more selective  
382 techniques such as monofilament fishing lines and purse seines (Chauveau et al., 2000; Thiao et al.,  
383 2017). Indeed, fisheries managers have not been able to effectively implement the law on the  $L_c$   
384 indicated by the Senegal's fisheries code. Most of the sardinella individuals landed in recent year are  
385 small (Sow et al., 2016), while the last indicator  $L_{c\_opt}$  (25 and 28 cm for *S. maderensis* and *S. aurita*,  
386 respectively) would help implement a fishing strategy that does not catch any mega-parent (Froese,  
387 2004). According to Froese et al. (2016), to obtain a maximum yield for a given  $F$ , the  $L_c$  can be  
388 increased to allow a longer non-exploited growth phase, until the exploitable biomass and therefore  
389 the catch per unit of effort (CPUE) reach a maximum. Therefore, any catch at  $L_{c\_opt}$ , close to  $L_c$  and  
390 therefore greater than the  $L_{50}$  of both sardinella (TL; 20 cm), could make it possible to better reach  
391 sustainability. However, the current governance framework of the sardinella fisheries does not allow  
392 for the definition and implementation of appropriate conservation and management measures for these  
393 shared stocks (sardinella species) because the existing regional body, like the Sub-Regional Fisheries  
394 Commission (SRFC), has only advisory mandates. The SRFC is not, yet, a Regional fisheries  
395 management organizations (RFMO). This situation is unfortunate because it does not comply with the  
396 provisions of the United Nations Convention on the Law of the Sea, which obliges States to consult  
397 each other and to endeavor to reach agreement in order to keep exploited populations within viable  
398 biological limits.

399 **5. CONCLUSION**

400 The Length-based Bayesian biomass (LBB) model provided a widely applicable and cost-effective  
401 starting point for use in establishing indicators for sustainable management of data-poor fisheries on  
402 tropical small pelagics. Its common use at least in West Africa will allow comparative analysis and  
403 thus provide better information to fisheries managers. Thus, to rebuild sardinella fisheries in Senegal,  
404 fisheries management should include: a revision of Senegal's fishing code, which should set a length at  
405 first capture  $\geq 18$  cm, is recommended by adopting  $L_c$  even if  $L_{c\_opt}$  should be a better option. Indeed,  
406 captured individuals at  $L_{c\_opt}$  (25 and 28 cm for *S. maderensis* and *S. aurita*, respectively) should be a  
407 natural safeguard against any failure of recruitment and to enable individuals to ensure the long-term  
408 survival of populations, in a context of data poor fisheries.

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431 **COMPETING INTERESTS**

432 The authors have declared that no competing interests exist.

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600 **Supplementary material**

601 Table 1: Size distribution (Total length) of *Sardinella maderensis* (n= 143,621) and *Sardinella aurita*  
 602 (n= 193,357) specimens collected in Senegalese waters from 2004 to February 2014. ML: Midpoint  
 603 Length (cm)

<i>Sardinella maderensis</i>												
ML	1	2	3	4	5	6	7	8	9	10	11	12
6	3	0	3	0	3	0	2	0	0	0	0	0
8	0	1	1	0	0	1	2	2	0	0	0	0
10	4	7	4	2	2	2	2	2	7	1	1	5
12	19	44	12	5	13	11	1	12	26	29	9	29
14	47	51	45	6	15	18	9	74	50	107	27	30
16	117	116	133	71	127	89	44	211	98	142	77	55
18	140	163	145	162	295	248	243	284	157	188	132	63
20	368	362	384	541	770	1285	791	1011	640	900	892	260
22	728	971	882	1042	1076	1900	1440	1320	750	1265	1514	648
24	871	1429	1443	999	763	1073	1286	997	674	618	957	708
26	1144	1827	1956	1272	1312	1427	2003	1451	1056	699	1232	1185
28	2448	2422	3253	2737	2678	2180	2164	1870	1127	1055	1451	2014
30	4249	4213	6061	4220	3082	1732	2238	2351	1268	914	1369	2397
32	2611	3038	4342	2464	1683	933	1544	1585	938	339	611	1112
34	986	1170	1325	1088	725	300	445	608	269	97	177	355
36	99	96	139	173	57	55	46	62	32	7	12	36
38	10	6	25	24	16	21	13	7	8	2	4	6
<i>Sardinella aurita</i>												
6	2	0	0	1	2	0	0	0	0	2	2	2
8	0	2	1	1	0	0	0	0	0	0	1	1
10	0	1	1	0	4	1	16	3	2	0	0	0
12	1	17	4	0	9	6	70	32	32	29	2	0
14	12	48	23	4	18	17	94	97	155	95	9	2
16	32	30	31	15	111	76	95	132	280	345	58	13
18	78	20	16	25	206	483	347	284	468	313	83	36
20	120	31	32	20	230	738	573	453	582	301	179	134
22	174	114	91	126	290	784	503	538	383	357	485	410
24	516	317	282	404	629	1051	897	586	399	561	1319	965
26	1595	1445	1216	1959	2399	1369	1455	791	551	927	3011	3418
28	2119	2045	2780	2110	2594	2059	1860	735	675	1061	2347	2956
30	3303	2912	3222	3574	3961	3604	2893	1528	748	2048	4006	4681
32	6355	5701	6129	8392	7506	4512	2620	1193	424	1274	3097	7541
34	3327	4396	5315	7376	5122	2337	1106	310	131	219	690	2700
36	407	847	1274	1365	789	207	66	20	8	15	51	203
38	24	58	57	51	45	18	12	1	8	2	18	35

604

## Figures captions

FIGURE 1: Map of the study area with the localization of sampling stations corresponding to the main landing ports along the Senegal coast. The northern section includes Saint-Louis, Kayar, and Yoff; the southern section includes the “Petite côte” (Hann, Mbour, and Joal) and Casamance (Kafountine).

FIGURE 2: Landing of sardinella species [*Sardinella aurita* (grey fill), *S. maderensis* (black fill)] of the artisanal fishery of Senegal (1981 to 2011). Data obtained from the Centre de Recherches Océanographiques de Dakar-Thiaroye (CRODT; Senegal).

FIGURE 3: Annual mean of both *Sardinella* lengths [*Sardinella maderensis* (black solid line,  $n = 143\ 562$ ) and *Sardinella aurita* (black dashed line,  $n = 193\ 283$ )] combined to Coastal Upwelling Index (CUI; grey solid line) and Sea Surface temperature (SST; grey dashed line) over the Senegalese continental shelf (data: 2004 to 2014).

FIGURE 4: The accumulated length data used to estimate priors Length at first capture ( $L_c$ ), asymptotic length ( $L_{inf}$ ), and  $Z/K$  for *Sardinella maderensis* (a) and *Sardinella aurita* (b). The blue line shows the exploited part of the population, meaning the population that is susceptible to the fishing gear.  $L_c$ : the length-at first capture i.e. the length at which 50% of the individuals are retained by the fishing net.  $L_{inf}$ : the maximum length of the fish species according to your data. ( $L_{inf}$  is actually the asymptotic length, but here approximated by the maximum observed length).

FIGURE 5: Isopleth diagrams of yield and biomass-per-recruit for *Sardinella maderensis* (a) and *Sardinella aurita* (b) in Senegal (data: 2004-2014).

FIGURE 6: Number of fishermen trips using the purse seines canoe for *Sardinella maderensis* (curve with cross) and *Sardinella aurita* (curve with circle) between 2004 and 2014 in Senegal over the main landing sites.

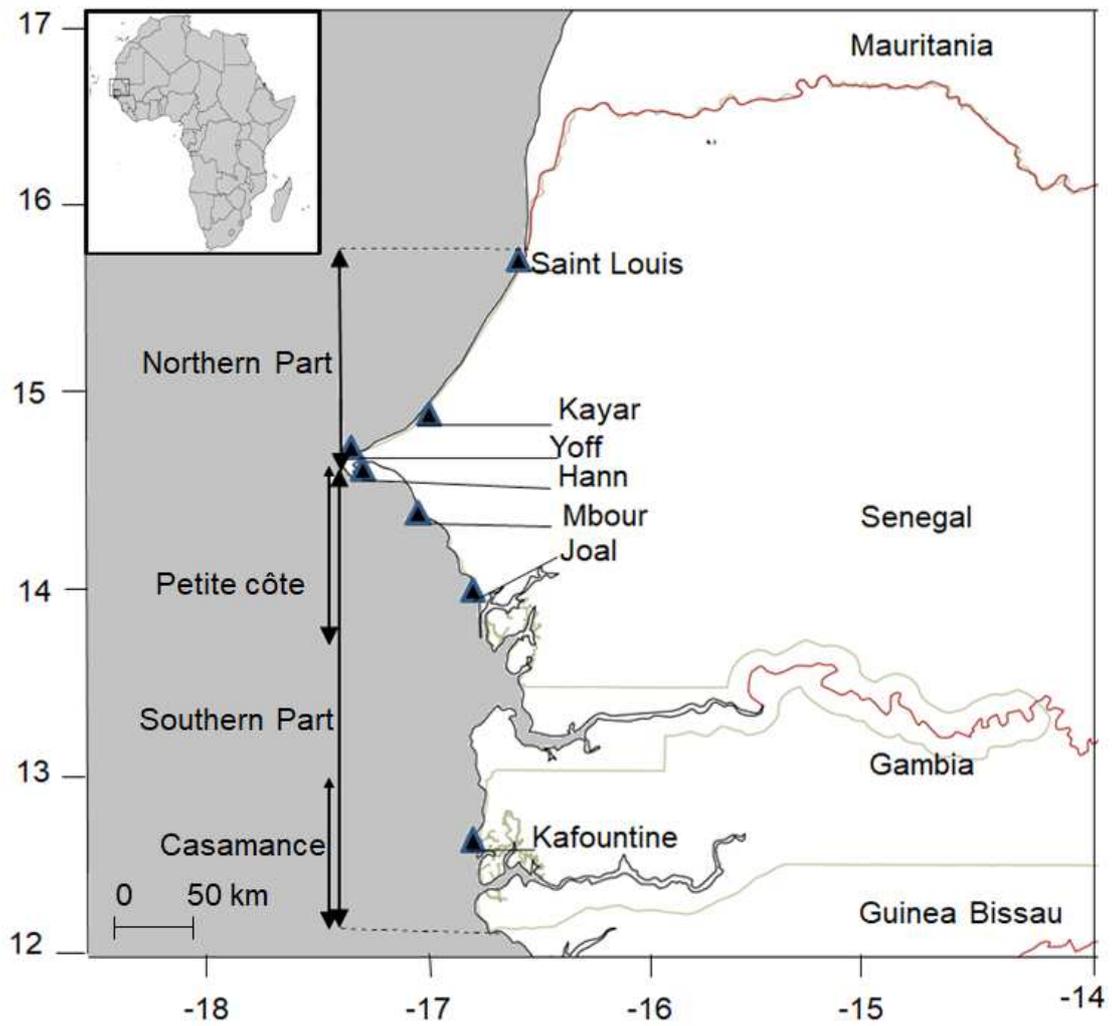


FIGURE 1:

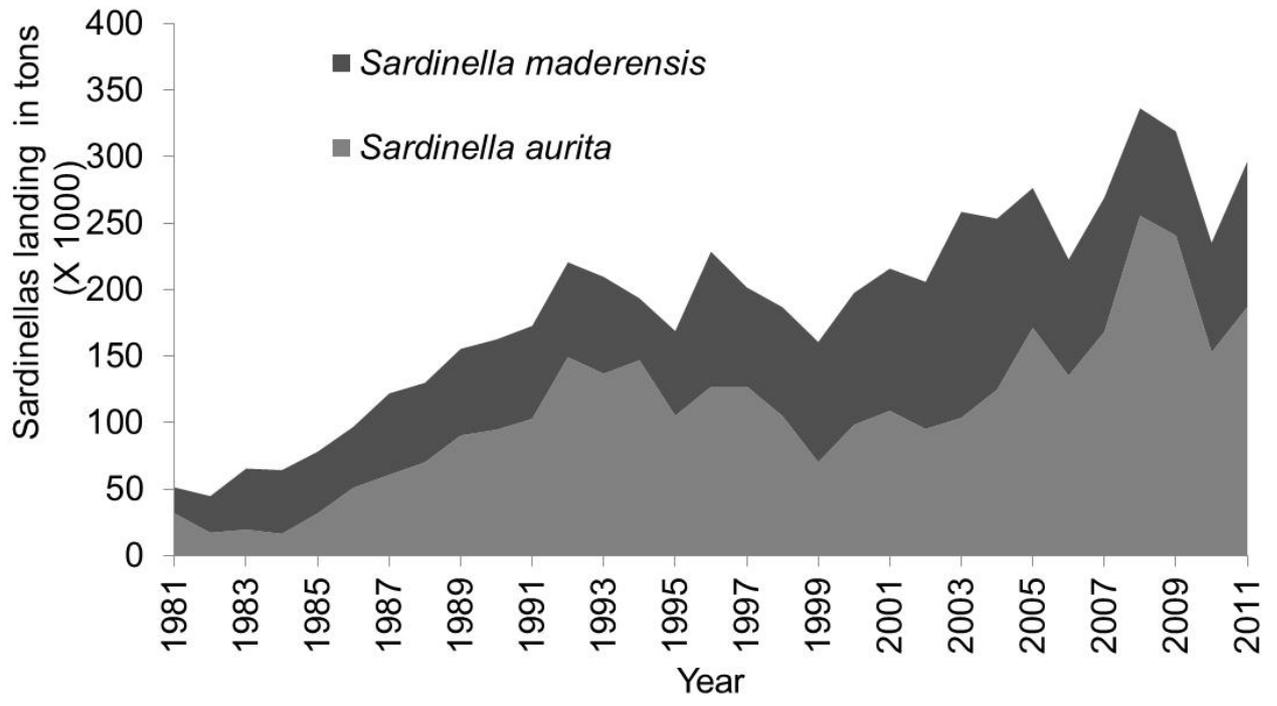


FIGURE 2:

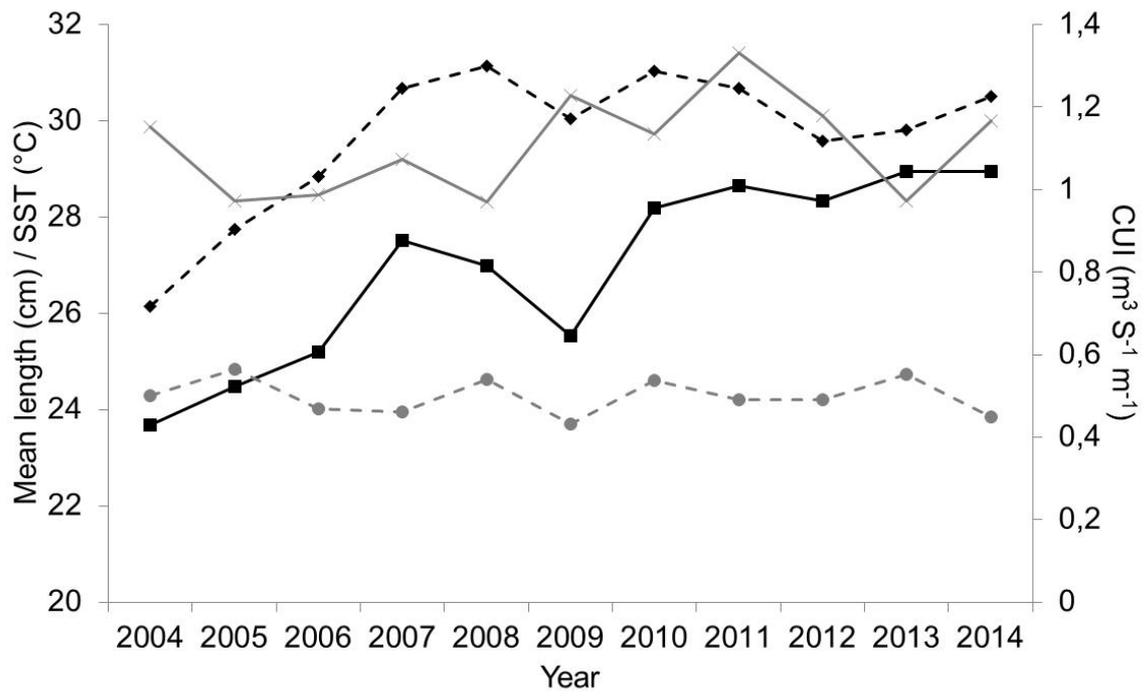
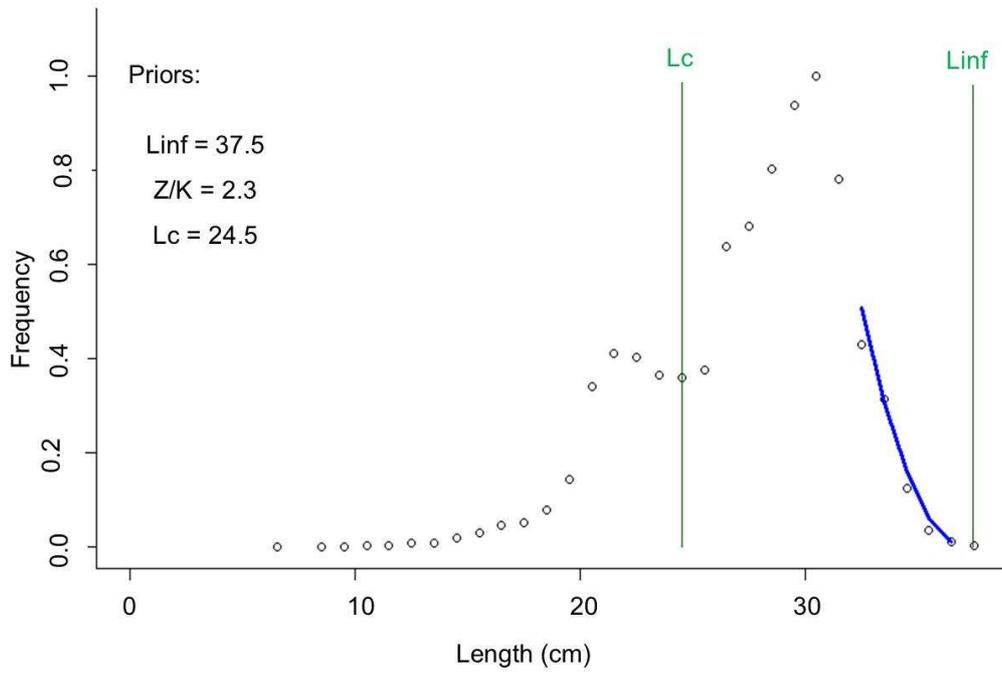
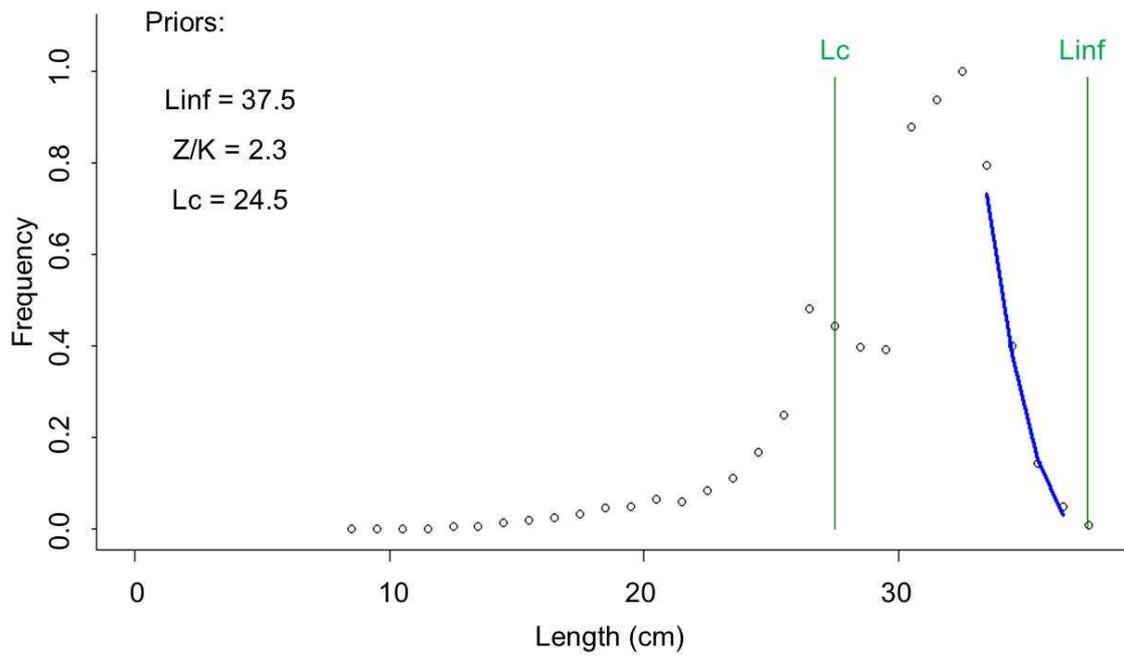


FIGURE 3

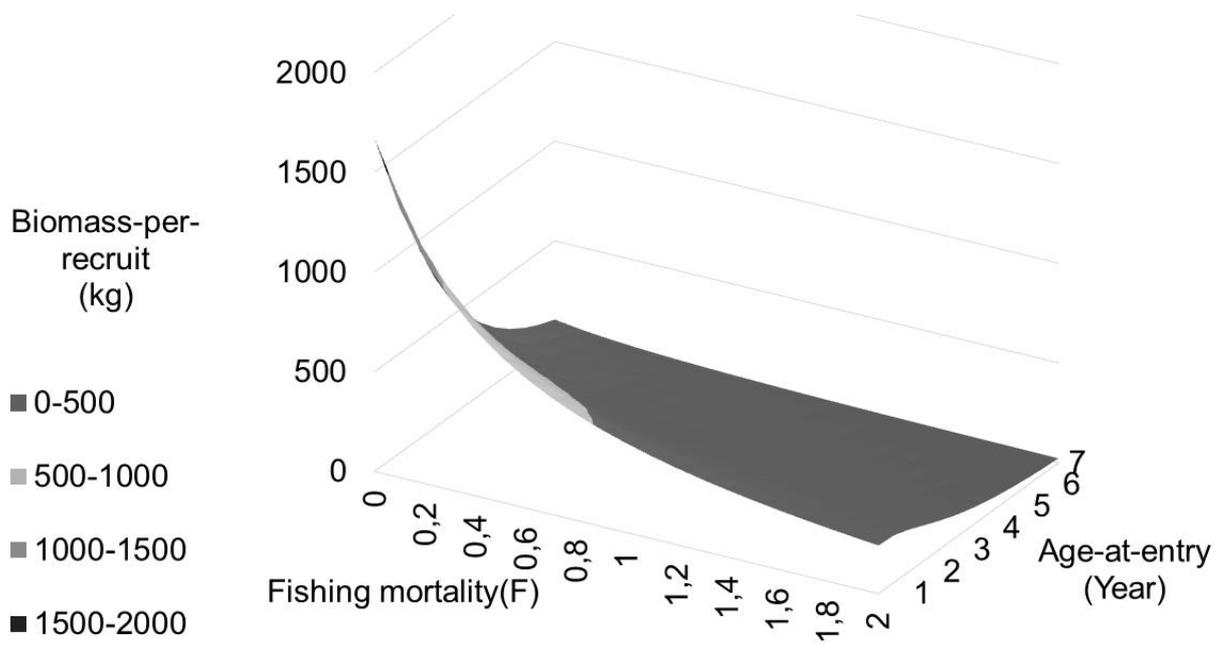
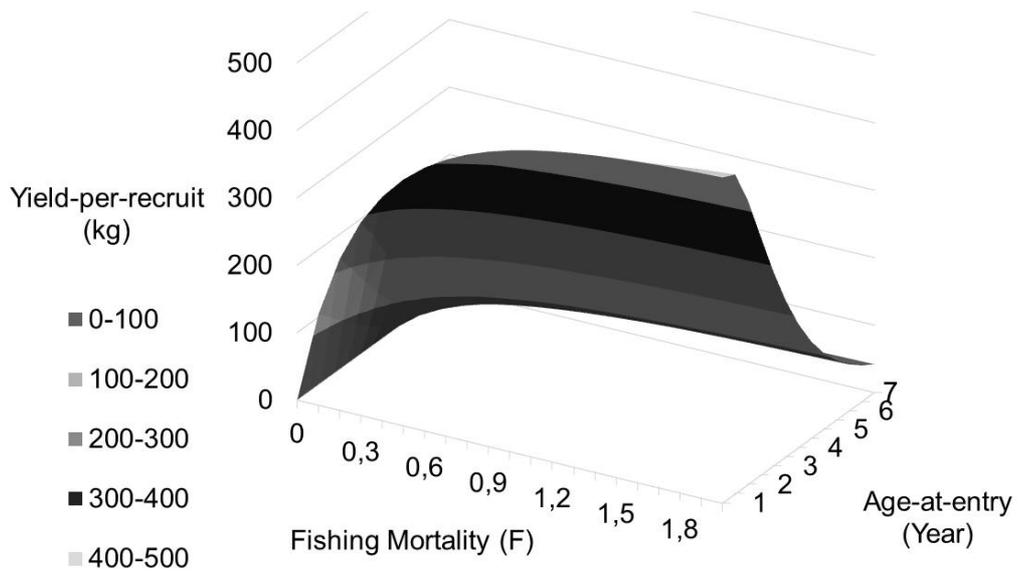


a)

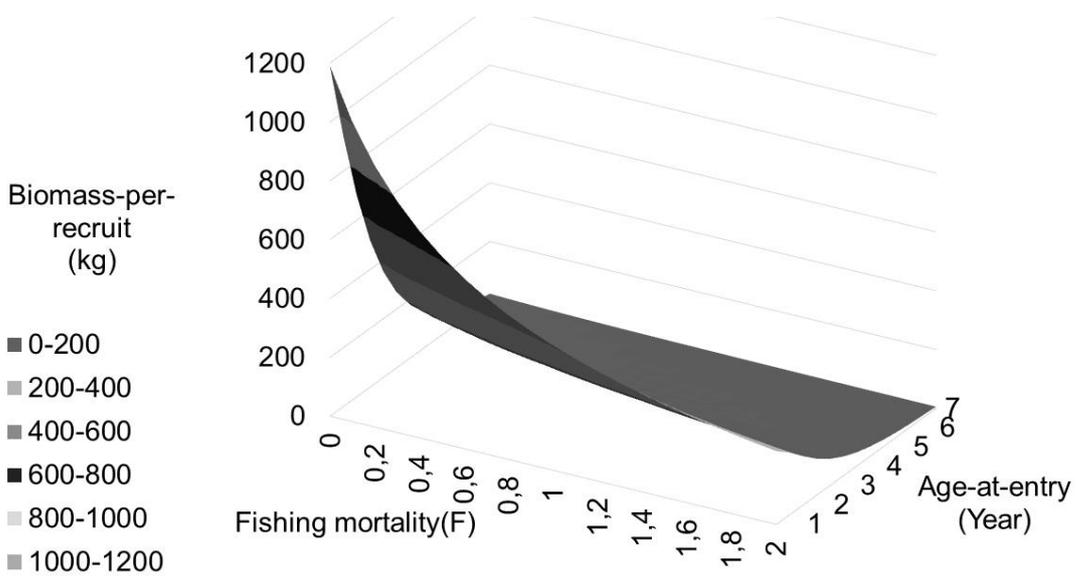
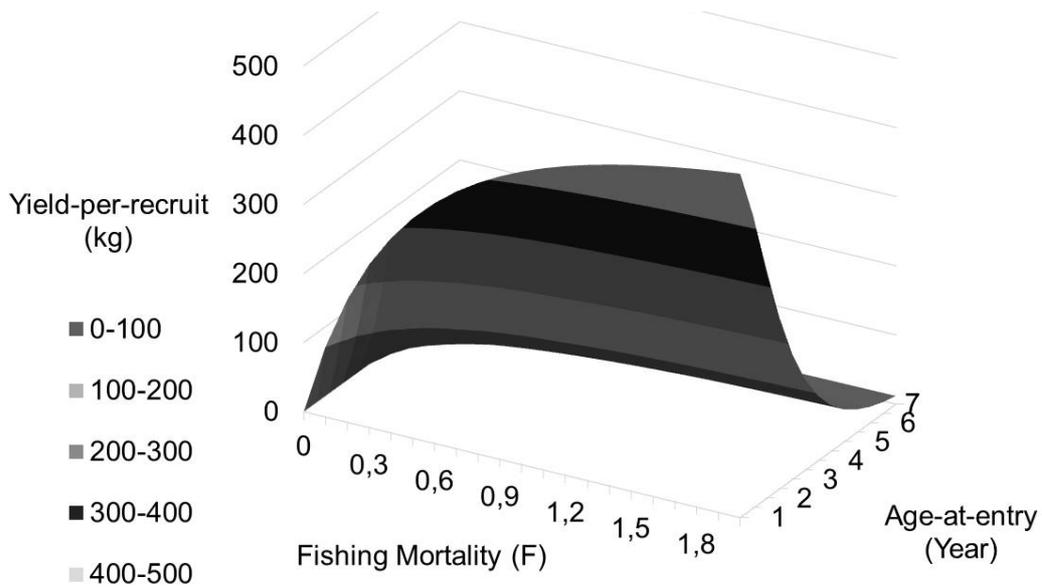


b)

FIGURE 4:



a)



b)

FIGURE 5:

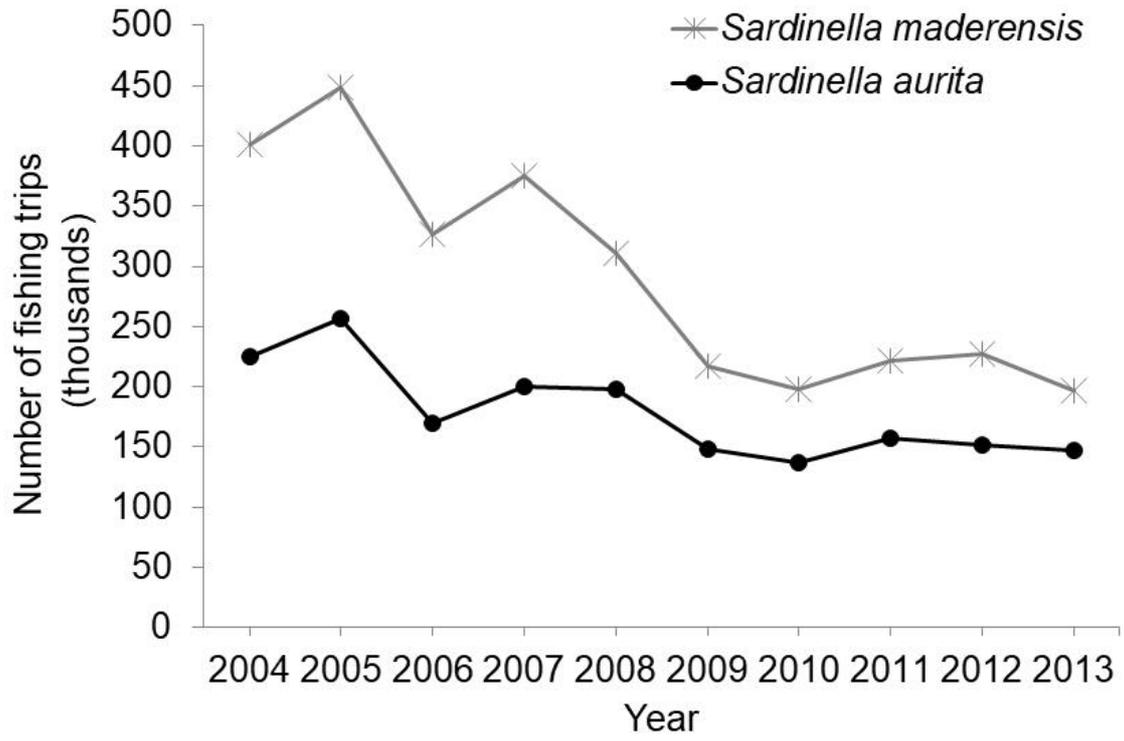


FIGURE 6:

TABLE 1: Number of individuals captured per port of landing during the study period (2004-2014) in Senegalese waters.

Port	<i>Sardinella maderensis</i>	<i>Sardinella aurita</i>
Hann	21187	22280
Joal	14896	11638
Kafountine	2201	342
Kayar	30735	70618
Mbour	10064	7318
Saint Louis	62452	72863
Yoff	2449	8224
Total	143984	193283

TABLE 2: Results of Pearson tests between mean annual length (TLm) of both sardinella and environmental parameters (CUI: Coastal Upwelling Index and SST: Sea Surface Temperature) observed in Senegal (2004-2014). N: Number of variables.

Species	Variables	N	t	df	R <sup>2</sup>	p-value
<i>Sardinella madarensis</i>	TLm.yr <sup>-1</sup> - CUI	11	0.76252	9	0.25	0.4653
	TLm.yr <sup>-1</sup> - SST	11	-0.051163	9	-0.02	0.9603
<i>Sardinella aurita</i>	TLm.yr <sup>-1</sup> - CUI	11	0.48828	9	0.16	0.637
	TLm.yr <sup>-1</sup> - SST	11	-0.44352	9	-0.15	0.6679

TABLE 3: Descriptive variables for *Sardinella maderensis* (SM; n= 143621) and *Sardinella aurita* (SA; n= 193357) specimens collected in Senegalese waters from January 2004 to December 2014.

Variable	Symbol	SM	SA
		Estimated value	
Asymptotic length (cm)	$L_{\infty}$	37.5	37.5
Asymptotic Weight (g)	$W_{\infty}$	1055	1055
Coefficient of growth rate ( $y^{-1}$ )	$K$	1.01	1.02
Time “t” when the fish length is zero	$t_0$	- 0.4	-0.6
Constant	$a$	0.02*	0.02*
Allometric coefficient	$b$	3.00*	3.00*
Natural mortality	$M$	0.5	0.7
Fishing mortality	$F$	1.8	1.7
Total mortality	$Z$	2.3	2.4
Length at first capture (cm)	$L_c$	24.5	27.5
Length-at-maturity (cm)	$L_{50}$	20.3*	20.3*
Mean age at first maturity ( $y^{-1}$ )	$t_m$	2	2
Species longevity ( $y^{-1}$ )	$t_{max}$	8.1	10.7
Unexploited cohort biomass reaches a maximum (g)	$W_{opt}$	667	568
Length at maximum possible yield per recruit (cm)	$L_{opt}$	26	29
Age at the peak of unexploited cohort biomass ( $y^{-1}$ )	$t_{opt}$	0.8	0.8
Mean catch length of $L_{opt}$ in exploited population (cm)	$L_{c\_opt}$	25	28
Time corresponding to $L_{c\_opt}$ ( $y^{-1}$ )	$t_{c\_opt}$	0.7	0.5
Index of yield per recruit ( $y^{-1}$ )	$Y'/R$	0.2	0.2
Exploitation rate	$E$	0.8	0.7

\* : Ba et al. 2016