Regional Studies In Marine Science
September 2019, Volume 31 Pages 100801 (10p.)
https://doi.org/10.1016/j.rsma.2019.100801
https://archimer.ifremer.fr/doc/00512/62318/

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

Baldé Bocar Sabaly [1, 2, 3? *], Fall Massal [1], Kantoussan Justin [4], Sow Fambaye Ngom [1], Diouf Malick [3], Brehmer Patrice [1, 2]

[1] Institut Sénégalais de Recherche Agricole (ISRA), Centre de Recherche Océanographique de Dakar-Thiaroye (CRODT), BP 2241, Centre PRH, Dakar, Senegal
[2] IRD, Univ Brest, CNRS, Ifremer, Lemar, Délégation Régional IRD Ouest, Plouzané, France
[3] Université Cheikh Anta Diop (UCAD), Institut Universitaire de Pêche et d'Aquaculture (IUPA), BP 45784, Dakar, Senegal
[4] Unité de Formation et de Recherche des Sciences Agronomiques, de l'Aquaculture et des Technologies Alimentaires (UFR S2ATA), Université Gaston Berger (UGB), Saint-Louis, Senegal

* Corresponding author : Bocar Sabaly Baldé, email address : bocarbalde2005@hotmail.com

Abstract :

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

Keywords : Data poor fisheries, Fisheries management, Shared stocks, Small scale fisheries, Small pelagic fish, West Africa

1. INTRODUCTION

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

For example, the length-based empirical estimation method of spawning potential ratio (LB-SPR) model implemented by Hordyk et al. (2014), estimates the length selectivity and the F/M ratio, which are then used to calculate the Stock Reproductive Potential Ratio (SPR). The SPR is defined as the proportion of unexploited breeding potential, regardless of the level of fishing pressure retained (Walters and Martell, 2004). This equilibrium-based method, which assumes constant recruitment, cannot accommodate multimodal length composition, a situation known as the "Lee's phenomenon" (Lee, 1912). As a result, any estimate of F/M ratio, selectivity, and SPR may be unrealistic. To cope with this handicap, Hordyk et al. (2016) developed a new length structured model using the Growth-Type-Group approach (GTG). Indeed, this new model has the particularity, compared to LB-SPR, of using the life-time ratio M/K, as well as estimates of the size at first maturity (L_{50}), the asymptotic length (L_∞) and the length composition, to estimate the potential spawning ratio with size-dependent selectivity models (Hordyk et al., 2016). However, in the case where the selectivity is not age-dependent, the results of the model may be strongly biased. Another model, Length-based Integrated Mixed Effects (LIME), is used to study age-structured population dynamics (Rudd and Thorson, 2017), while taking into account variable fishing mortality and recruitment over time, which makes it different from the two models mentioned above (LB-SPR and GTG). For the LIME model, the input parameters are data on the length composition of catches for a given year as well as information on the assumed life cycle, including the length-age relationship, an assumed natural mortality rate, and a length at 50% of maturity (Rudd and Thorson, 2017). However this model works well only for fish with a short life span. The higher the age of the fish, the greater the uncertainty becomes. Indeed, the increasing length makes cohorts unclear with age, making it difficult to track recruitment events without a much longer time series of length data (Rudd and Thorson, 2017). And like LB-SPR and GTG, LIME requires setting biological parameters and good knowledge of species biology to their true value for estimating unbiased reference points.

Thereby, a new model based solely on length frequencies called Length-based Bayesian biomass (LBB) seems to be an interesting option for estimating tropical and subtropical stocks poor in data (Froese et al., 2018). However, Hordyk et al. (2019) found that LBB model has some major problems such as the values of the M / K relationship that can change depending on the species exploited. As a result, a misinterpretation of values of this relationship can bias the results. Froese et al. (2019) indicates that these parameters can be taken into account by LBB model users and modified according to the available information. According to Froese et al. (2018), this model is a length-based Bayesian estimator that further reduces data requirements for preliminary stock assessments. The LBB model assumes that most tropical and subtropical species reach maximum size at maximum age. This implies that somatic growth and natural mortality of adults are aligned so that they can be expressed in a constant ratio (Froese et al., 2018). In tropical areas such as West Africa where species growth is rapid (*e.g.*, Ba et al., 2016; Baldé et al., 2019) and mortality is growth dependent (*Z/K*) (Froese et al., 2018), the LBB model appears to be more appropriate. This model was largely developed by Froese et al. (2018) and may be useful to provide management options for stocks with limited catch data. The LBB allows a simple analysis of size frequency data to obtain the length at first capture that would maximize catch and biomass for the given fishing effort, and provides an estimation of a proxy for the relative biomass capable of producing maximum sustainable yields. The model only requires length frequency data, length at first maturity (L_{50}) and life cycle parameters as inputs. LBB model estimates percentage of mature individuals, relative natural mortality (M) and relative fishing mortality (F) as means over the age range represented in the length-frequency sample (Froese et al., 2018).

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

2. MATERIAL AND METHODS

2.1. Study area

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

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

The Casamance (13 ° 04 N and 12 ° 20 N, Figure 1) is located between the borders of The Gambia and Guinea Bissau. The continental shelf reaches its maximum width, at nearly 54 miles and the rocky bottoms are located offshore, mainly on the edge of the plateau. Its estuary is in fact an estuary which runs for 250 km inside the continent (Sakho, 2011). It receives inputs of fresh water only during the rainy season which lasts only 5 months, from June to October. The climate is mainly characterized by the alternation of a hot wet season from around July to October and a cold dry season from around November to June. During the dry season, the many small streams that form the Casamance River are often dry. Declining rainfall in the Casamance River Basin and increased temperature have resulted in a runoff deficit and saline intrusion (Thiam and Singh, 2002).

2.2. Study species

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

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

2.3. Biological data

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

2.4. Environmental data

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

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

Where

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

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

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

Where W_t is the body weight at age t, W_∞ 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).

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

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

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

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

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

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

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

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

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

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

The age t_{c_opt} corresponding to L_{c_opt} is obtained by:

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

Total mortality (Z) can be measured by:

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

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

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

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

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

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

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

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 is the summation parameter (U_0=l, U_1=-3, U_2=3, U_3=-1) and F is the fishing mortality coefficient.

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

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

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 function of *F* (Eskandari et al., 2013; Pitcher, 1999). The yield isopleths diagram of *S. maderensis* and *S. aurita* was used to assess the impact on yield created by changes of exploitation rate *E* and the ratio of length at first capture to asymptotic length (L_c / L_∞) in relation to changes in mesh size (Ama-Abasi et al., 2004; Pauly and Soriano, 1986).

2.6. Statistical analysis

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

3. RESULTS

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

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

3.2. Fishing mortality and exploitation rate for both sardinella

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 and 0.7 for *S. maderensis* and *S. aurita*, respectively (Table 3). The F/M ratio was higher for *S. aurita* (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. maderensis* and *S. aurita*, respectively (Figure 4). For *S. maderensis* and *S. aurita*, the current rates of exploitation (E) in Senegal waters were 0.8 and 0.7, respectively. The yield contour predicts the response of the yield-per-recruit to changes in L_c and rate of exploitation E; L_c / L_∞ = 0.7 and 0.8 for *S. maderensis* and *S aurita*, respectively.

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

The von Bertalanffy equations fit well with the observed data ($R^2 \geq 0.90$ in all cases except in 2004 and $R^2 = 0.70$ for *S. maderensis* and *S. aurita*, respectively). Asymptotic length (L_∞) for the entire period was 37.5 cm (TL) for both sardinella while L_c was 24.5 and 27.5 cm (TL) for *S. maderensis* and *S. aurita*, respectively (Figure 4). Our growth studies, indicate that growth of *S. aurita* and *S. maderensis* (K = 1.01 and 1.02, respectively) in Senegal is fast. The likelihood ratio test indicated that there was no difference between the K and L_∞ values of both sardinella species, which implies that they follow the same pattern of growth. When L_{50} were 20.3 cm for both sardinella species, 95 and 92% mature individuals are observed for the entire study period for *S. maderensis* and *S. aurita*, respectively.

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

Changes of Y/R and B/R for *S. maderensis* and *S. aurita* according to various values of F and t_c are given in Figure 5. For *S. maderensis*, when M = 0.5, Y/R (564 kg; Figure 5a) and B/R (2,862 kg; Figure 5b) reach its maximum when t_c = 2.5 year^{-1}. While *S. aurita*, Y/R reached its maximum value (426 kg) after two to three years (t_c) when M was 0.7 (Figure 5a) and B/R decreased rapidly as F increased. Maximum B/R occurred at t_c < 2.5 years^{-1} (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 pallasi*), 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 environmental variables influencing the recruitment success are different for both studied species: the Coastal Upwelling Index and the SST for *S. aurita* and *S. maderensis*, respectively. Thus, we assume that the environmental variability can also have a significant impact on both sardinella species growth variability.

4.2. Diagnosis of sardinella fisheries

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

The *F/M* ratio is high for *S. maderensis* (*F/M* = 3.6) and *S. aurita* (*F/M* = 2.4). This comes from the change of fishing techniques and the motorization of the Senegalese canoes in recent years. In fact, the Senegalese canoe fleets are by far the most important in the West African region (including Nigeria and Ghana). In 2005, the number of fishing units was estimated to 13, 900 while the last census in 2015 reported 18,284 fishing units, including more than 90% motorized canoes (Sow et al., 2016). The dynamism of the artisanal fisheries resides in its capacity to adapt permanently to the changes of the context of the activity. This adaptive capacity depends on the qualitative and quantitative of the resource availability, economic context with reference to the possibilities of flow of the products and the levels of market remuneration (Binet et al., 2012). The strong reactivity of the Senegalese artisanal fishermen is linked, among others, to their good knowledge of the behavior of the resources but also their great organizational capacities to deal with changing institutional environment and appropriation of new techniques to exploit new resources (Binet et al., 2012). Given the level of exploitation of these species and the development and modernization of small-scale fisheries, indicators based on length-frequencies should help sustainable management at a critical time for these fisheries.

4.3. Indicators for sustainable management

One of the objectives of fisheries management is to minimize the impact of fishing on the size and age structure of exploited populations (Froese et al., 2016). Indeed, fishing with no size limit further reduces biomass, especially if higher values of M and hence of F are applied to pre-recruits (Froese et al., 2015). In Senegal, according to the 2015 Fishing code, the mesh size allowed for sardinella fisheries is restricted between 40 and 60 mm that represents a fish size TL $\geq$ 18.0 cm. Nevertheless, the average sizes of individuals caught in both sardinella species are smaller than the L_{50} of 20.3 cm (TL) (Ba et al., 2016). In the long-term, this fact could prevent the sustainability of sardinella stocks because it does not allow them to renew properly. Indeed, sardinella species show patterns of spatial and temporal distribution by size group (Ba et al., 2016; Baldé et al., 2019). Indicators based on length- frequencies can be used to establish management measures for fisheries (Froese, 2004; Froese et al., 2016). The L_c found in our study is higher than the L_c indicated by the Senegalese fishing code (TL $\geq$ 18.0 cm) and also the L_{50} (20.3 cm) for both sardinella species found by Ba et al. (2016). Fishing at L_c (24.5 and 27.5 cm for *S. maderensis* and *S. aurita*, respectively) would allow all fish to reproduce at least once before being caught. This will result in rebuilding and maintaining reproductive stocks in good health. However, such a tactic is only possible if the recruitment is successful each year. According to Diankha et al. (2018), the recruitment of *S. maderensis* and *S. aurita* in Senegal is subject to variation depending on the sea surface temperature and the coastal upwelling index, respectively. As a result, the environment will have to be taken into account in this sustainable fishery hypothesis. The second indicator L_{opt} (26 and 29 cm for *S. maderensis* and *S. aurita*, respectively) is the length where maximum yield can be obtained. This focus on large specimens is based on the growing evidence that older fish play several important roles in the long-term survival of a population (*e.g.*, egg production; Baldé et al., 2019). This size (L_{opt}) is greater than L_c found in our study, therefore greater than L_c indicated by the Senegalese fishing code and the L_{50} of both sardinella. However, the realities of Senegalese fisheries must be taken into account. In fact, to cope with the scarcity of resources, Senegalese fishermen are increasingly using more selective techniques such as monofilament fishing lines and purse seines (Chauveau et al., 2000; Thiao et al., 2017). Indeed, fisheries managers have not been able to effectively implement the law on the L_c indicated by the Senegal's fisheries code. Most of the sardinella individuals landed in recent year are small (Sow et al., 2016), while the last indicator L_{c_opt} (25 and 28 cm for *S. maderensis* and *S. aurita*, respectively) would help implement a fishing strategy that does not catch any mega-parent (Froese, 2004). According to Froese et al. (2016), to obtain a maximum yield for a given *F*, the L_c can be increased to allow a longer non-exploited growth phase, until the exploitable biomass and therefore the catch per unit of effort (CPUE) reach a maximum. Therefore, any catch at L_{c_opt}, close to L_c and therefore greater than the L_{50} of both sardinella (TL; 20 cm), could make it possible to better reach sustainability. However, the current governance framework of the sardinella fisheries does not allow for the definition and implementation of appropriate conservation and management measures for these shared stocks (sardinella species) because the existing regional body, like the Sub-Regional Fisheries Commission (SRFC), has only advisory mandates. The SRFC is not, yet, a Regional fisheries management organizations (RFMO). This situation is unfortunate because it does not comply with the provisions of the United Nations Convention on the Law of the Sea, which obliges States to consult each other and to endeavor to reach agreement in order to keep exploited populations within viable biological limits.

5. CONCLUSION

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

ACKNOWLEDGEMENTS

Data analysis was done inside the AWA project funded by IRD and the BMBF (grant 01DG12073E, 01DG12073B), www.awa.ird.fr (SRFC: Sub Regional Fisheries Commission), the Preface project funded by the European Commission's Seventh Framework Program (2007-2013) under Grant Agreement number 603521, https://preface.b.uib.no/ and the DAAD program under Grant Agreement number 57314022. The data for this study were collected through the CRODT (Senegal) fisheries information system from 2004–2014. We are thankful to all CRODT technicians for their professionalism during the data collection on the field all the year around. We also thank the editor Gunnar Lauenstein and three anonymous reviewers for their useful comments on this manuscript.

Author contributions

Conceptualization: BSB JK.

Data curation: BSB JK FB.

Formal analysis: BSB JK.

Methodology: BSB JK.

Project administration: BSB PB.

Resources: BSB.

Software: BSB JK.

Validation: PB MF FB.

Supervision: PB MF MD.

Visualization: BSB.

Writing – original draft: BSB JK.

Writing – review & editing: BSB JK PB.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

REFERENCES

Ama-Abasi, D., Holzloehner, S., Enin, U., 2004. The dynamics of the exploited population of *Ethmalosa fimbriata* (Bowdich, 1825, Clupeidae) in the Cross River Estuary and adjacent Gulf of Guinea. Fish. Res. 68, 225–235. https://doi.org/10.1016/j.fishres.2003.12.002

Auger, P.-A., Gorgues, T., Machu, E., Aumont, O., Brehmer, P., 2016. What drives the spatial variability of primary productivity and matter fluxes in the North-West African upwelling system? A modelling approach and box analysis. Biogeosciences 13, 6419–6440.

Ba, K., Thiaw, M., Lazar, N., Sarr, A., Brochier, T., Ndiaye, I., Faye, A., Sadio, O., Panfili, J., Thiaw, O.T., others, 2016. Resilience of Key Biological Parameters of the Senegalese Flat Sardinella to Overfishing and Climate Change. PloS One 11, e0156143.

Baldé, B.S., 2019. Dynamique des petits poissons pélagiques (*Sardinella aurita* et *Ethmalosa fimbriata*) au Sénégal dans un contexte de changement climatique : diagnostic et synthèse bioécologiques. Université Cheikh Anata Diop, Dakar, Senegal.

Baldé, B.S., Brehmer, P., Sow, F.N., Ekau, W., Kantoussan, J., Fall, M., Diouf, M., 2018. Population dynamics and stock assessment of *Ethmalosa fimbriata* in Senegal call for fishing regulation measures. Reg. Stud. Mar. Sci. 24, 165–173.

Baldé, B.S., Döring, J., Ekau, W., Diouf, M., Brehmer, P., 2019. Bonga shad (*Ethmalosa fimbriata*) spawning tactics in an upwelling environment. Fish. Oceanogr. 00, 1–12. https://doi.org/10.1111/fog.12451

Baldé, B.S., Sow, F.N., Ba, K., Ekau, W., Brehmer, P., Kantoussan, J., Fall, M., Diouf, M., 2019. Variability of key biological parameters of round sardinella *Sardinella aurita* and the effects of environmental changes. J. Fish Biol. 94, 391–401. https://doi.org/10.1111/jfb.13903

Ben-Tuvia, A., 1960. Synopsis on the systematics and biology of *Sardinella maderensis* (Lowe). Fisheries Division, Biology Branch, Food and Agriculture Organization of the United Nations.

Beverton, R.J., Holt, S.J., 1966. Manual of methods for fish stock assessment: Part 2-tables of yield functions (Fisheries Report No. 38). FAO, Rome.

Beverton, R.J., Holt, S.J., 1957. On the dynamics of exploited fish populations, Fishery Investigations. Ministry of Agriculture, Fisheries, and Food, London.

Beverton, R.J.H., 1992. Patterns of reproductive strategy parameters in some marine teleost fishes. J. Fish Biol. 41, 137–160.

Binet, T., Failler, P., Thorpe, A., 2012. Migration of Senegalese fishers: a case for regional approach to management. Marit. Stud. 11, 1.

Boëly, T., 1979. Biologie de deux espèces de sardinelles *Sardinella aurita* Valenciennes, 1847 et Sardinella maderensis Lowe, 1841 des côtes sénégalaises (Thèse de doctorat). Université Paris VI, Paris.

Boltachev, A.R., Karpova, E.P., 2014. Faunistic revision of alien fish species in the Black Sea. Russ. J. Biol. Invasions 5, 225–241.

Chauveau, J.-P., Jul-Larsen, E., Chaboud, C., others, 2000. Les pêches piroguières en Afrique de l'Ouest: dynamiques institutionnelles–pouvoirs, mobilités, marchés, C. Chaboud. ed. Karthala Editions, Paris.

Diankha, O., Ba, A., Brehmer, P., Brochier, T., Sow, B.A., Thiaw, M., Gaye, A.T., Ngom, F., Demarcq, H., 2018. Contrasted optimal environmental windows for both sardinella species in Senegalese waters. Fish. Oceanogr. 27, 351–365. https://doi.org/DOI: 10.1111/fog.12257

Eskandari, G., Koochaknejad, E., Hashemi, S.A., Mayahi, Y., 2013. Yield and Biomass-per-recruit Analysis of Tiger Tooth Croaker (*Otolithes ruber*) in the Northwest of the Persian Gulf. J. Persian Gulf 3, 1.

FAO, 2016. Report of the FAO working group on the assessment of small pelagic fish off Northwest Africa Casablanca, Morocco, 20–25 July 2015/ Rapport du groupe de travail de la FAO sur l'évaluation des petits pélagiques au large de l'Afrique Nord-Occidentale Casablanca, Maroc, 20-25 juillet 2015 (Casablanca, Maroc: FAO). (No. 1122). FAO, Casablanca, Maroc.

Faye, S., Lazar, A., Sow, B.A., Gaye, A.T., 2015. A model study of the seasonality of sea surface temperature and circulation in the Atlantic North-eastern Tropical Upwelling System. Front. Phys. 3, 76. https://doi.org/10.3389/fphy.2015.00076

Felder, D.L., 2009. Gulf of Mexico origin, waters, and biota: Biodiversity, College Station. ed, Biodiversity. Texas A&M University Press, Texas.

Froese, R., 2004. Keep it simple: three indicators to deal with overfishing. Fish Fish. 5, 86–91.

Froese, R., Pauly, D., 2016. FishBase: World Wide Web Electronic Publication Version [WWW Document]. URL http://www.fishbase.org (accessed 12.2.17).
Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A.C., Dimarchopoulou, D., Scarcella, G., Probst, W.N., Dureuil, M., Pauly, D., 2019. On the pile-up effect and priors for Linf and M/K: response to a comment by Hordyk et al. on “A new approach for estimating stock status from length frequency data.” ICES J. Mar. Sci. 7, 461–465. https://doi.org/10.1093/icesjms/fsy199
Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A.C., Dimarchopoulou, D., Scarcella, G., Probst, W.N., Dureuil, M., Pauly, D., 2018. A new approach for estimating stock status from length frequency data. ICES J. Mar. Sci. https://doi.org/10.1093/icesjms/fsy078
Froese, R., Winker, H., Gascuel, D., 2015. Size still matters. A response to Svedäng (2013): Size matters: Ne quid nimis. Fish. Res. 164, 329–330.
Froese, R., Winker, H., Gascuel, D., Sumalia, U.R., Pauly, D., 2016. Minimizing the impact of fishing. Fish Fish. 17, 785–802.
Haist, V., Stocker, M., 1985. Growth and maturation of Pacific herring (*Clupea harengus pallasi*) in the Strait of Georgia. Can. J. Fish. Aquat. Sci. 42, s138–s146.
Harrell Jr, F.E., 2017. with contributions from Charles Dupont and many others: Hmisc: Harrell Miscellaneous. R package version 3.17-2.
Hixon, M.A., Johnson, D.W., Sogard, S.M., 2014. BOFFFFs: on the importance of conserving old-growth age structure in fishery populations. ICES J. Mar. Sci. J. Cons. 71, 2171–2185.
Holt, S.J., 1958. The evaluation of fisheries resources by the dynamic analysis of stocks, and notes on the time factors involved. ICNAF Spec. Publ. 1, 77–95.
Hordyk, A., Ono, K., Valencia, S., Loneragan, N., Prince, J., 2014. A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. ICES J. Mar. Sci. 72, 217–231.
Hordyk, A.R., Ono, K., Prince, J.D., Walters, C.J., 2016. A simple length-structured model based on life history ratios and incorporating size-dependent selectivity: application to spawning potential ratios for data-poor stocks. Can. J. Fish. Aquat. Sci. 73, 1787–1799.
Hordyk, A.R., Prince, J.D., Carruthers, T.R., Walters, C.J., 2019. Comment on “A new approach for estimating stock status from length frequency data” by Froese et al. (2018). ICES J. Mar. Sci. 76, 457–460. https://doi.org/10.1093/icesjms/fsy168
Lee, R.M., 1912. An investigation into the methods of growth determination in fishes by means of scales. ICES J. Mar. Sci. 1, 3–34.
Marchal, E., 1991. Nanisme et sédentarité chez certaines espèces de. ORSTOM 201–208.
McDonald, J.H., 2009. Handbook of biological statistics. Sparky House Publishing Baltimore, MD, Baltimore, Maryland, USA.
McQuinn, I.H., Cleary, L., O’Boyle, R.N., 1990. Estimation de la mortalité naturelle, in: Méthodes d’évaluation Des Stocks Halieutiques. Projet CIEO-860060, Centre International d’Exploitation des Oceans, Halifex, Nouvelle- Ecosse, Canada, pp. 441– 464.
Mildenberger, T.K., Taylor, M.H., Wolff, M., 2017. TropFishR: an R package for fisheries analysis with length-frequency data. Methods Ecol. Evol. https://doi.org/10.1111/2041-210X.12791
Ndoye, S., Capet, X., Estrade, P., Sow, B., Dagorne, D., Lazar, A., Gaye, A., Brehmer, P., 2014. SST patterns and dynamics of the southern Senegal-Gambia upwelling center. J. Geophys. Res. Oceans 119, 8315–8335.
Ndoye, S., Capet, X., Estrade, P., Sow, B., Machu, E., Brochier, T., Döring, J., Brehmer, P., 2017. Dynamics of a “low-enrichment high-retention” upwelling center over the southern Senegal shelf. Geophys. Res. Lett. 44. https://doi.org/10.1002/2017GL072789
Nguyen, T.H., Brochier, T., Auger, P., Trinh, V.D., Brehmer, P., 2018. Competition or cooperation in transboundary fish stocks management: Insight from a dynamical model. J. Theor. Biol. 447, 1–11.
Pauly, D., 1983. Some simple methods for the assessment of tropical fish stocks (Fisheries Report No. 234). FAO, Rome.
Pauly, D., Soriano, M.L., 1986. Some practical extensions to Beverton and Holt’s relative yield-per-recruit model, in: Maclean, J.L., Dizon, L.B., Hosillo, L.V. (Eds.), The First Asian Fisheries Forum. Manila: Asian Fisheries Society, Philippines, pp. 491–496.
Pitcher, T.J., 1999. Beverton and Holt equations: spreadsheet functions and uncertainty. Naga ICLARM Q. 22, 37–41.

Roy, C., Cury, P., Fontana, A., Belvèze, H., 1989. Stratégies spatio-temporelles de la reproduction des clupéidés des zones d'upwelling d'Afrique de l'Ouest. Aquat. Living Resour. 2, 21–29.
Rudd, M.B., Thorson, J.T., 2017. Accounting for variable recruitment and fishing mortality in length-based stock assessments for data-limited fisheries. Can. J. Fish. Aquat. Sci. 75, 1019–1035.
Sakho, I., 2011. Évolution et fonctionnement hydro-sédimentaire de la lagune de la Somone, Petite Côte, Sénégal. Université de Rouen; Université Cheikh Anta Diop de Dakar, Sénégal.
Sarré, A., 2017. Approche acoustique de la dynamique et la distribution spatiale des ressources halieutiques de petits pélagiques dans l'upwelling sénégalo-mauritanien (PhD Thesis). Université de Bretagne Occidentale, Brest, France.
Sokal, R.R., Rohlf, F.J., 1995. Biometry, W. H. Freeman. ed. Freeman, New York.
Sow, F.N., Thiaw, M., Mbaye, A., 2016. Appui à la mise en place des plans de gestion des petits pélagiques au Sénégal (Rapport No. 1). Centre de Recherche Océanographique Dakar Thiaroye, Dakar, Senegal.
Stilwell, J., 2008. Sustainable development and the governance of fisheries frequented by heterogeneous user groups: a political economy perspective on the case of European Union participation in the Senegalese marine fishery. Paris: Université de Versailles St-Quentin-en-Yvelines.
Sylla, M., Brochier, T., Pecquerie, L., Ndiaye, O., Richaume, M., Brehmer, P., 2016. Senegalese *Sardinella aurita* from 1995 to 2011: review of size spectra, sex ratio, gonadal somatic and condition indexes from small scale main national landing sites, in: International Conference ICAWA 2016 : Extended Book of Abstract : The AWA Project : Ecosystem Approach to the Management of Fisheries and the Marine Environment in West African Waters. Presented at the International Conference AWA (ICAWA), SRFC/CSRP; IRD, Dakar, Senegal, pp. 51–51.
Team, Rs., 2015. RStudio: integrated development for R. RStudio Inc, MA, Boston.
Thiam, E.-H.I., Singh, V.P., 2002. Space-time-frequency analysis of rainfall, runoff and temperature in the Casamance River basin, southern Senegal, West Africa. Water SA 28, 259–270.
Thiao, D., 2012. Bioécologie et exploitation des petits pélagiques au sénégal. Sub-Regional Fisheries Commission, Dakar.
Thiao, D., Mbaye, A., Dème, M., Diadhiou, H.D., 2017. Focusing on monofilament nets while overlooking the priorities of artisanal fisheries governance in Senegal. Afr. J. Mar. Sci. 39, 339–348.
Thiao, D., Sow, F.N., Thiam, N., Fall, M., Thiam, M., 2016. Statistiques de la pêche maritime sénégalaise en 2015 : Pêche artisanale, Pêche thonière et Pêche chalutière (Archives Scientifiques No. 226). Institut Sénégalais Recherches Agricoles (ISRA), Centre de Recherches Océanographiques de Dakar-Thiaroye (CRODT), Sénégal.
Thiaw, M., Auger, P.-A., Sow, F.N., Brochier, T., FAYE, S., Diankha, O., Brehmer, P., 2017. Effect of environmental conditions on the seasonal and inter-annual variability of small pelagic fish abundance off North-West Africa: the case of both Senegalese sardinella. Fish. Oceanogr. 26, 583–601. https://doi.org/10.1111/fog.12218
Thorson, J.T., Cope, J.M., 2015. Catch curve stock-reduction analysis: an alternative solution to the catch equations. Fish. Res. 171, 33–41.
Tiedemann, M., Brehmer, P., 2017. Larval fish assemblages across an upwelling front: Indication for active and passive retention. Estuar. Coast. Shelf Sci. 187, 118–133.
Tiedemann, M., Fock, H.O., Brehmer, P., Döring, J., Möllmann, C., 2017. Does upwelling intensity determine larval fish habitats in upwelling ecosystems? The case of Senegal and Mauritania. Fish. Oceanogr. 26, 655–667.
von Bertalanffy, L., 1938. A quantitative theory of organic growth (inquiries on growth laws. II). Hum. Biol. 10, 181–213.
Walters, C.J., Martell, S.J., 2004. Fisheries ecology and management. Princeton University Press, Princeton (New Jersey).
Whitehead, P.J.P., 1985. An annotated and illustrated catalogue of the Herrings, Sardines, Pilchards, Sprats, Shads, Anchovies and Wolf-Herrings. Part 2, Engraulidae, in: FAO Species Catalogue, Clupeoid Fishes of the World. FAO, Rome, pp. 1–303.
Zar, J.H., 2014. Biostatistical Analysis: Pearson New International Edition, 5th ed. Pearson Education Limited, Harlow, UK.

Supplementary material

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

Sardinella maderensis												
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
Sardinella aurita												
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

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).

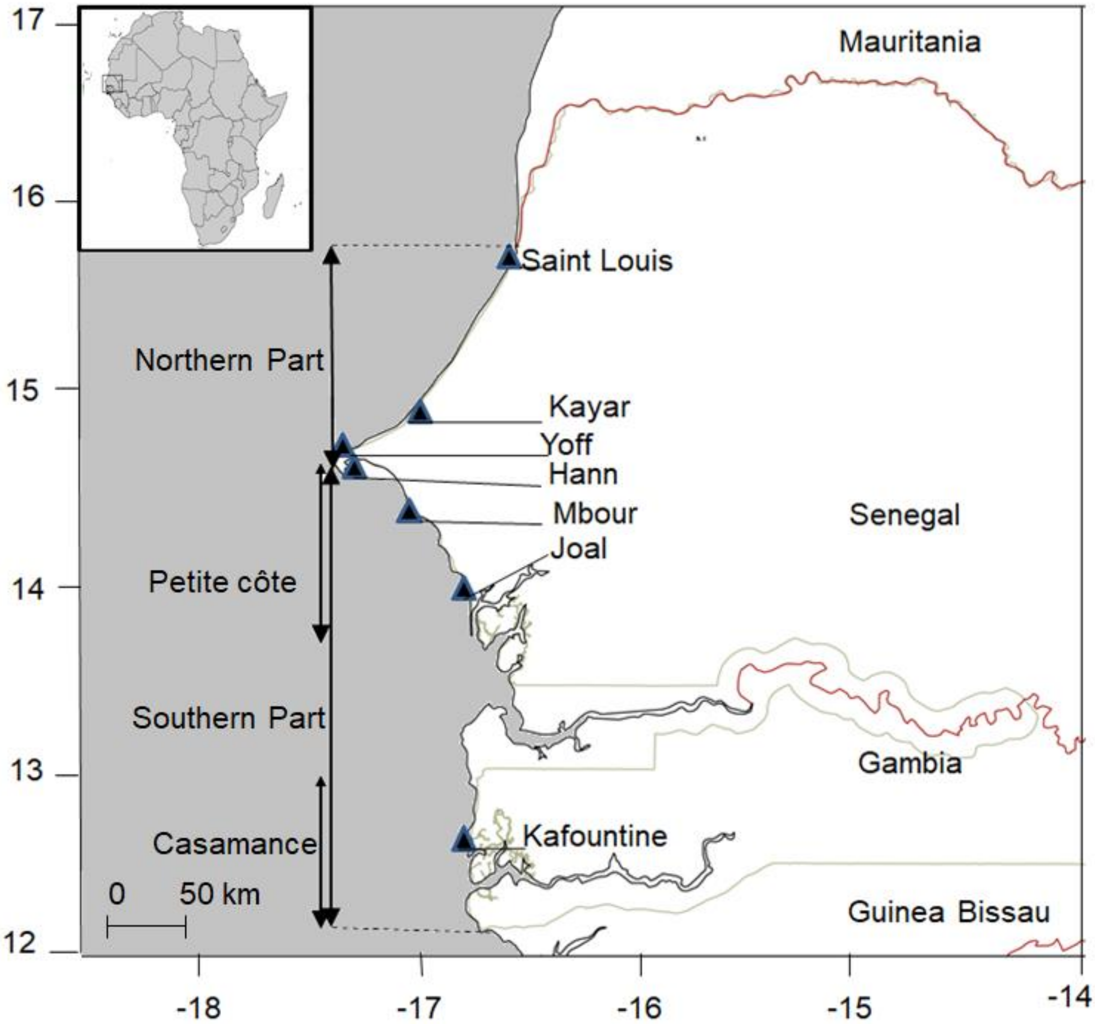
FIGURE 2: Landing of sardinella species [*Sardinella aurita* (grey fill), *S. maderensis* (black fill) of the artisanal fishery of Senegal (1981 to 2011). Data obtained from the Centre de Recherches Océanographiques de Dakar-Thiaroye (CRODT; Senegal).

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.



17
16
15
14
13
12
-18
-17
-16
-15
-14
Mauritania
Saint Louis
Northern Part
Kayar
Yoff
Hann
Mbour
Joal
Senegal
Petite côte
Southern Part
Gambia
Casamance
Kafountine
0
50 km
Guinea Bissau

FIGURE 1:

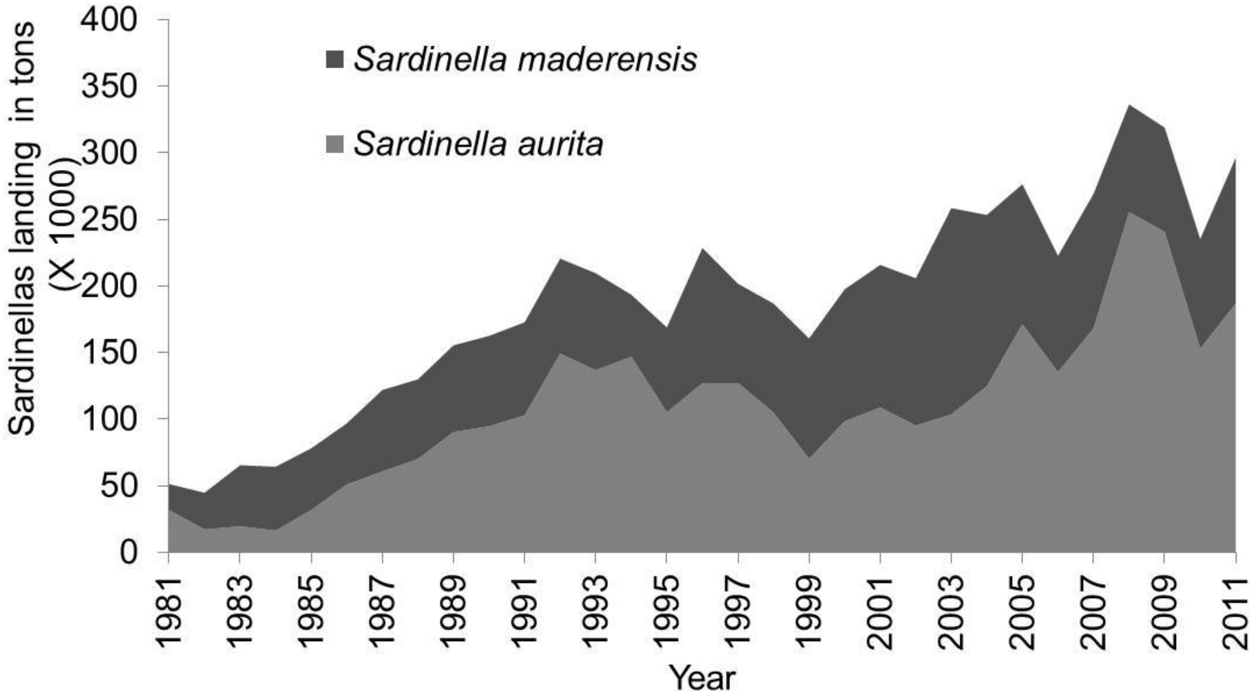

Sardinella maderensis
Sardinella aurita
Sardinellas landing in tons (X 1000)
400
350
300
250
200
150
100
50
0
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
Year

FIGURE 2:

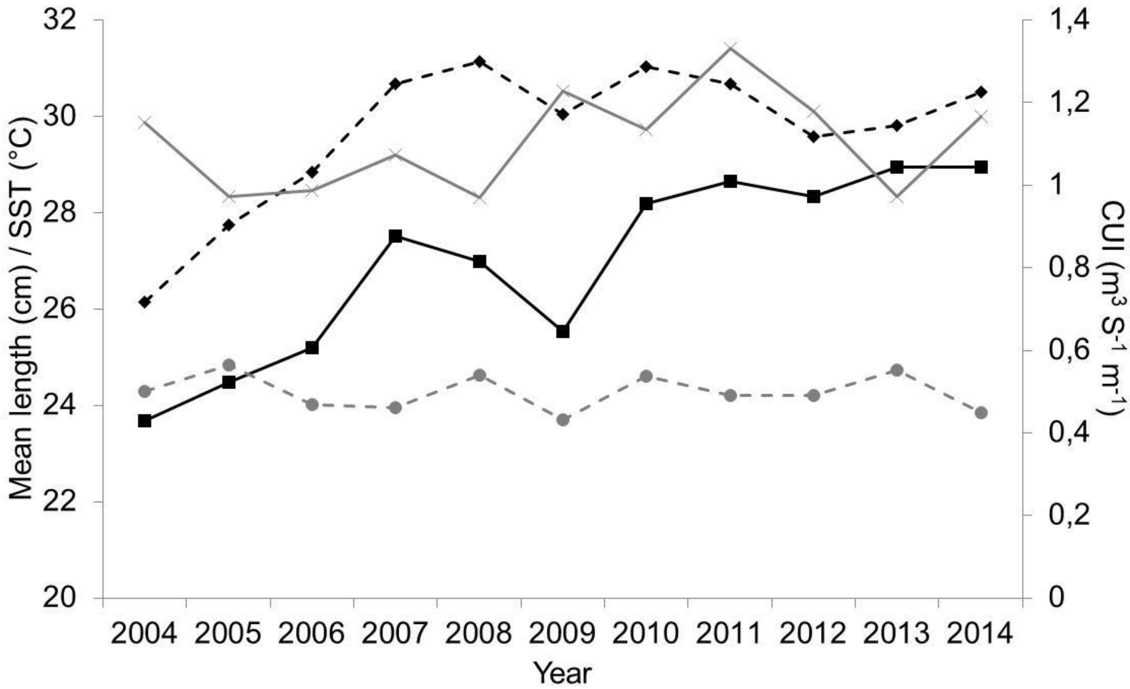
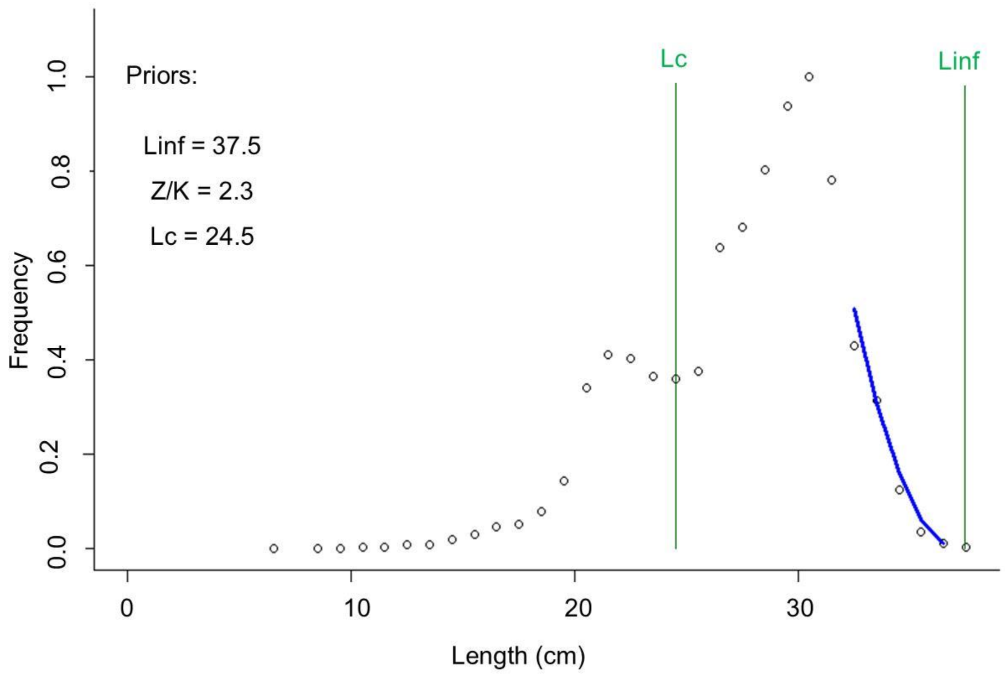
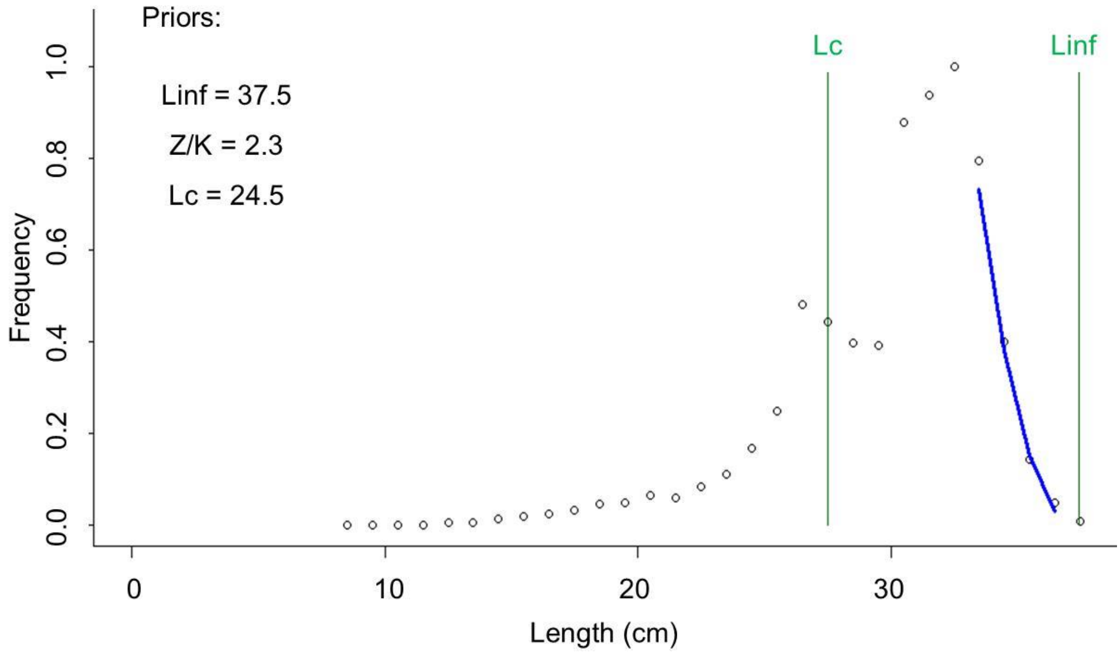

32
30
28
26
24
22
20
Mean length (cm) / SST (°C)
1,4
1,2
1
0,8
0,6
0,4
0,2
0
CUI ($m^3 S^{-1} m^{-1}$)
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Year

FIGURE 3

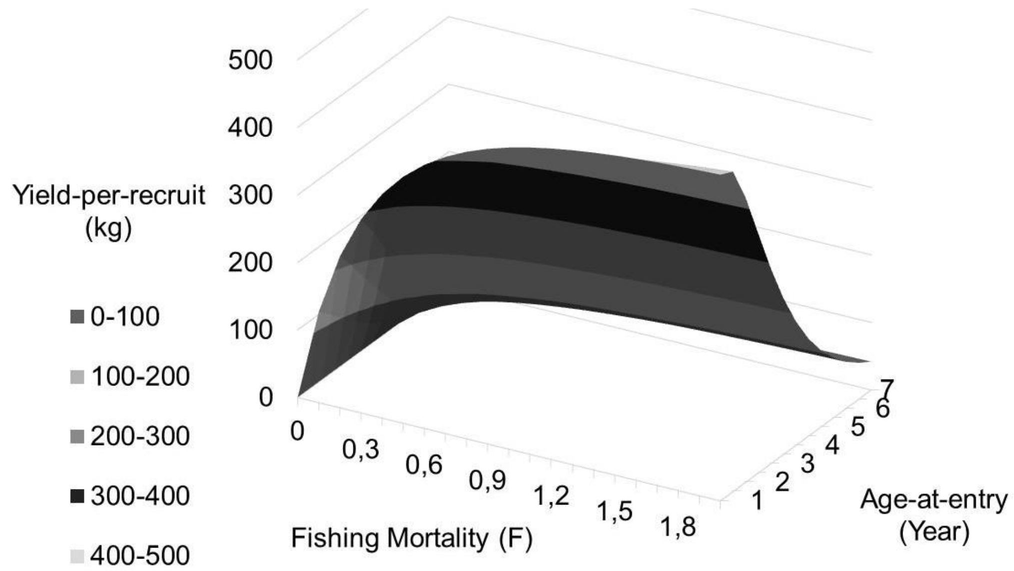

Priors:
Linf = 37.5
Z/K = 2.3
Lc = 24.5
Lc
Linf
Frequency
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
Length (cm)

a)

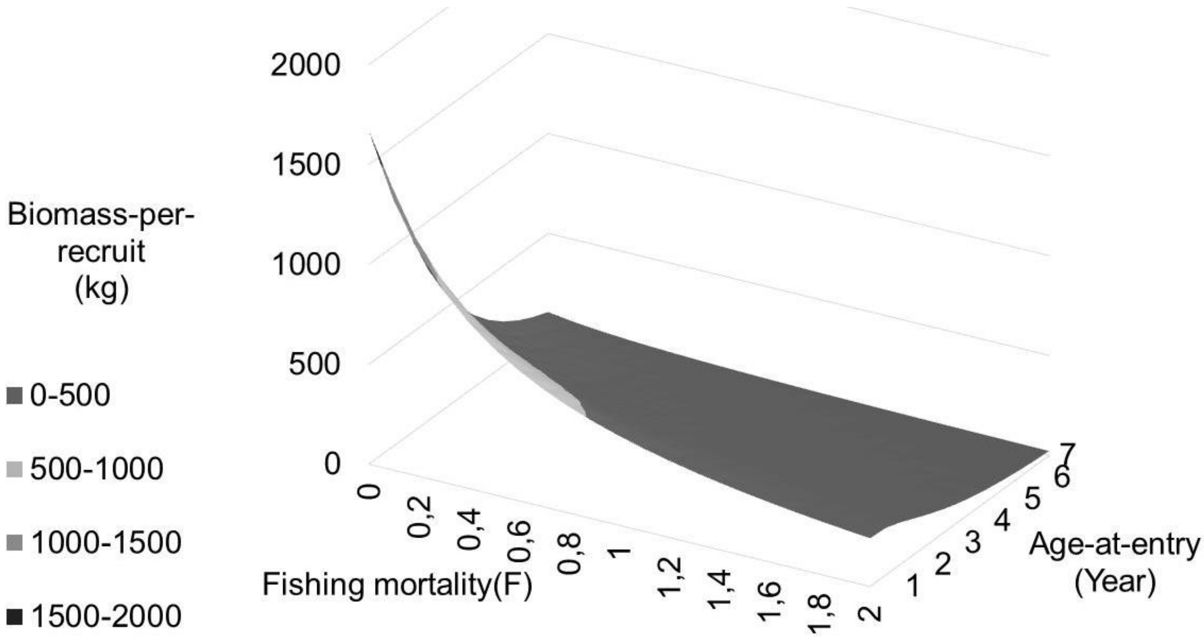

Priors:
Linf = 37.5
Z/K = 2.3
Lc = 24.5
Lc
Linf
Frequency
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
Length (cm)

b)

FIGURE 4:

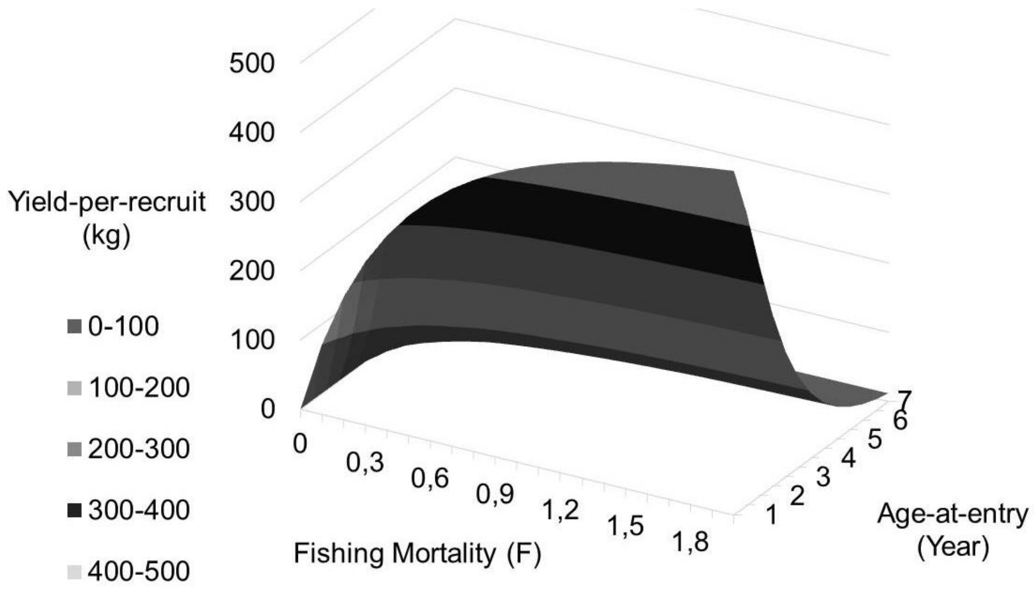


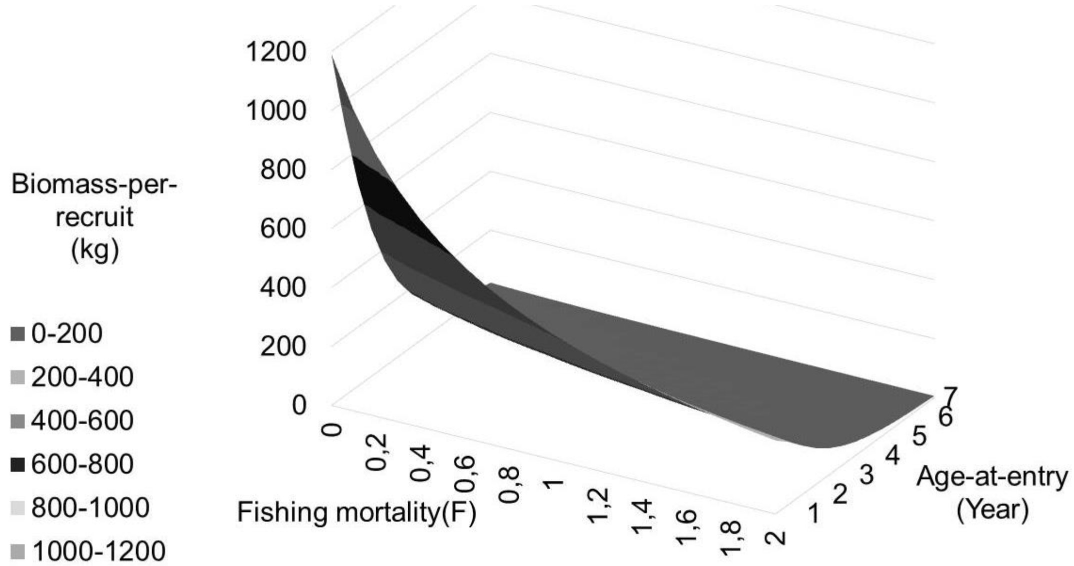
500
400
300
200
100
0
Yield-per-recruit
(kg)
0-100
100-200
200-300
300-400
400-500
0
0,3
0,6
0,9
1,2
1,5
1,8
Fishing Mortality (F)
1
2
3
4
5
6
7
Age-at-entry
(Year)



2000
1500
1000
500
0
Biomass-per-
recruit
(kg)
0-500
500-1000
1000-1500
1500-2000
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Fishing mortality(F)
1
2
3
4
5
6
7
Age-at-entry
(Year)

a)


Yield-per-recruit (kg)
0-100
100-200
200-300
300-400
400-500
500
400
300
200
100
0
0
0,3
0,6
0,9
1,2
1,5
1,8
Fishing Mortality (F)
1 2 3 4 5 6 7
Age-at-entry (Year)


Biomass-per-recruit (kg)
0-200
200-400
400-600
600-800
800-1000
1000-1200
1200
1000
800
600
400
200
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Fishing mortality(F)
1 2 3 4 5 6 7
Age-at-entry (Year)

b)

FIGURE 5:

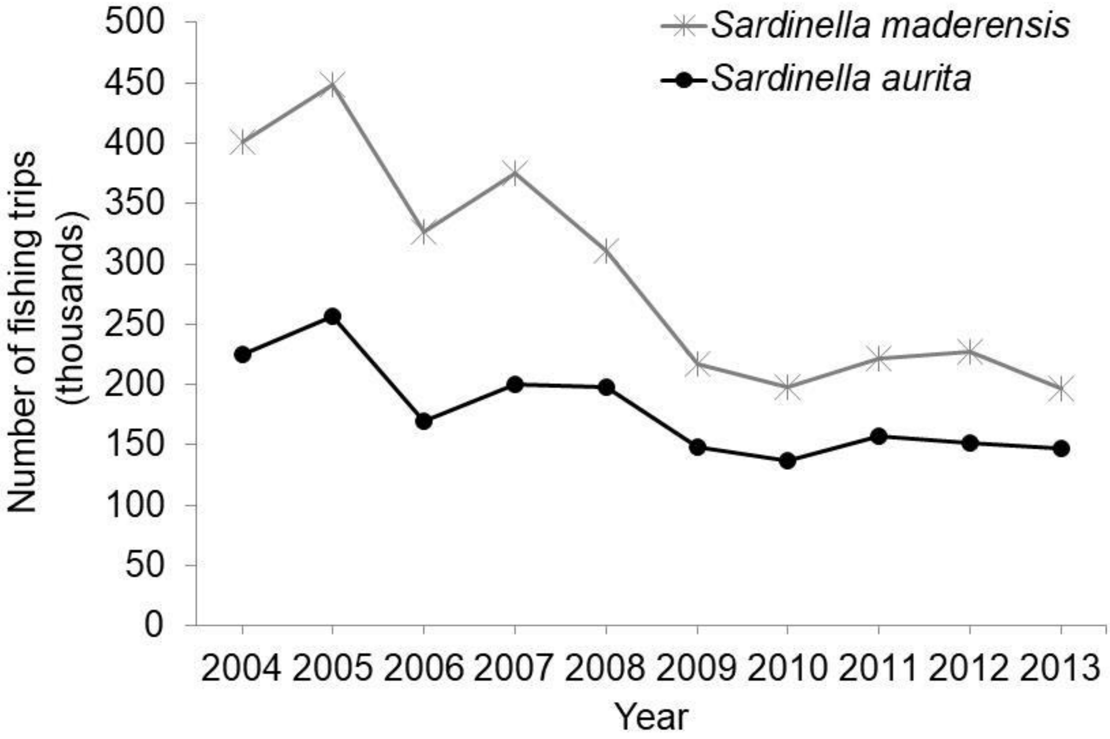

Sardinella maderensis
Sardinella aurita
Number of fishing trips (thousands)
500
450
400
350
300
250
200
150
100
50
0
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Year

FIGURE 6:

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

Port	*Sardinella maderensis*	*Sardinella aurita*
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^2	p-value
Sardinella madarensis	TLm.yr^{-1} - CUI	11	0.76252	9	0.25	0.4653
	TLm.yr^{-1} - SST	11	-0.051163	9	-0.02	0.9603
Sardinella aurita	TLm.yr^{-1} - CUI	11	0.48828	9	0.16	0.637
	TLm.yr^{-1} - 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_∞	37.5	37.5
Asymptotic Weight (g)	W_∞	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 Lopt 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