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Overexploitation of round sardinella may lead to the collapse of flat sardinella: What lessons can be drawn for shared stocks

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ABSTRACT

This paper describes the fisheries and presents quantitative stock assessments for two stocks of *Sardinella* in the waters of NW Africa. More robust stock assessments are now possible because of improved sampling in Mauritania and Senegal. Round sardinella (*S. aurita*), which has a wider distribution than flat sardinella (*S. maderensis*), is the most important species targeted by the different artisanal and industrial fleets. The industrial fleet is located beyond 13 miles from the coast, taking mainly adults. The average size in the offshore fishery, although it has decreased, remains above 26 cm. The species is also exploited by an artisanal fleet using small purse seiners. Two types of assessment model were applied: a production model and size-based model. The abundance indices were consistent, and showed a continuous decline, increasing in rate in recent years. The Just Another Bayesian Biomass Assessment (JABBA) model (applied for the first time) appeared to be appropriate for the abundance indices (Root Mean Squared Error (RMSE) 18.3–19.2 % for the two models). The results of the two models are consistent in showing increasing fishing mortality and declining biomass for both stocks over the time series. According to the JABBA model, the situation for the round sardinella stock is now critical (biomass at approximately 5 % of unexploited biomass (B0) and 10 % of biomass capable of producing maximum sustainable yields (Bmsy), with fishing mortality 2.5 times above Fmsy), and the flat sardinella is also overfished and suffering massive overfishing (B estimated at 18 %B0 and 25 %Bmsy, with fishing mortality more than 11 times above Fmsy). The results of the Length-based Bayesian Biomass (LBB) model are much more optimistic. It still concludes that both stocks are suffering overfishing (round sardinella F at ~1.4 times Fmsy proxy, flat sardinella ~2.2 times Fmsy proxy), but estimates that only the flat sardinella is overfished (B 28%B0 and 80 %Bmsy), while the round sardinella stock is not overfished (B 40 %B0 and 120 %Bmsy). However, these results are not consistent with the abundance index from acoustic surveys (used in the JABBA model) and overall are thought to be less robust. Signs of heavy exploitation have been observed for round sardinella for several years. This situation has been exacerbated since the arrival in late 2016 in the Mauritanian zone of efficient semi-industrial purse seiners targeting small pelagics. The various indirect assessment models used show a difficult stock situation for the round sardinella, on which many fishing communities in the area depend. Abundance indices from acoustic survey confirm the state of overexploitation of this resource. This situation has directed effort towards the flat sardinella, which is characterized by a more coastal distribution and limited migration. This species has been showing signs of overexploitation since 2019. We highlight this result for flat sardinella, which was previously not thought to be overexploited, and propose that managers should also consider how the estimated maximum sustainable catch and fishing mortality can be appropriately distributed between the different fleets in different countries, to ensure that future industry planning in the countries of the region is compatible with the sustainability of these critical stocks. This is a very complex task, as it involves not only discussions between

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neighboring countries, but also difficult decisions within countries about the economic and socio-economic importance of different fisheries sectors. It is essential that these reflections start immediately.

1. Introduction

The EEZ of the Islamic Republic of Mauritania is the epicentre of an area of very high productivity and biodiversity, thanks to a set of hydro-physical, climatic and morphological conditions generating upwelling, as well as the thermal front between the Guinea and Canary currents (Braham et al., 2014; Modou et al., 2017). These conditions produce a wealth of fisheries that present a great opportunity to Mauritania both for its economic development and for the food security of its populations. The sectoral policies adopted by the different governments have set objectives for sustainable management of the resources and a better integration of the sector into the national economy (MPEM, 2022).

The small pelagic stocks in Mauritania are shared by other countries in the region; Morocco in the north and Senegal and the Gambia in the south. Within the total range of this distribution area, the species are exploited by artisanal, coastal and industrial fleets, both national and foreign. They are the most important species in terms of landings (tonnage and significance for the local economy) (Braham and Corten, 2015; Ba et al., 2016; FAO, 2021). These species are gregarious, relatively short-lived and have high natural mortality. They undergo trophic and reproductive migrations linked to variations in marine environmental conditions (Modou et al., 2017; Diankha et al., 2018).

The increased demand for these species in recent years has created a critical situation for the main pelagic stocks, including the two sardinella species (round sardinella and flat sardinella). The situation raises several questions about the management and development of the fisheries, such as how the allocation of catches should be arranged, and how fishing effort can be reduced Fig. 1.

The sardinella caught in the Mauritanian zone are composed of two species, namely the round sardinella (*Sardinella aurita*) and the flat sardinella (*Sardinella maderensis*). Acoustic surveys show that these two species are distributed over a vast area ranging from the southern part of Morocco to the south of Senegal. The two sardinella species show the most direct need for sub-regional management. The transboundary nature of the stocks has led to a scramble in which each coastal state tries to extract the maximum amount of sardinella when the fish are in their area.

The pressure on these stocks has further increased not only because of the emergence of fish meal and oil factories in some countries but also because of the arrival of semi-industrial purse seiners and pelagic trawlers. For this reason, the FAO Working Group on Small Pelagics in Northwest Africa has repeatedly sounded the alarm that the round sardinella resources of the sub-region are overexploited (e.g. FAO, 2016, Baldé et al., 2022). If the current trend continues or worsens further, coastal nations engaged in fishing will be deprived of a vital source of food, income, and employment .

The objective of this paper is to carry out a diagnosis of the status of the stocks of the two sardinella species (round sardinella and flat sardinella) focusing on the Mauritanian area, which is main feeding and reproduction area in the region (Braham et al., 2014; Timothée Brochier). In addition, the work analyzes the consequences of the overexploitation of the round sardinella and its impact on the closely related flat sardinella; the distribution of which partly overlaps with that of the round sardnella.

2. Background to the study

2.1. Characteristics of the two sardinella species

Both sardinella species are similar in size and appearance; the main distinguishing feature is the black spot on the operculum of the round sardinella. On the flat sardinella, the black spot is not on the operculum but rather just behind.

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Round sardinella are generally found further offshore than flat sardinella but may also concentrate along the coast when food production declines in the offshore area (Corten et al., 2012). Round sardinella make extensive seasonal migrations (north/south) while flat sardinella are known to be more sedentary (Boely et al., 1982), resulting potentially in a more complex stock structure. In general, round sardinella have a higher market value than flat sardinella although during some seasons fish processors prefer flat sardinella due to the fact that it contains less fat and thereby is more suitable for smoking and drying. Braham (2013) and Jeyid (2016) assumes the existence of a sedentary stock of round sardinella with limited migration in the Mauritania zone. This hypothesis is confirmed by a recent work on nursery and spawning areas in the Mauritanian zone which suggests the existence of three critical sites to be protected (IMROP, 2020).

2.2. Small pelagic fisheries in the sub-region

In Mauritania, the two species of sardinella are exploited by an artisanal purse seine fishery in Senegalese-type pirogues, an inshore semi-industrial ('coastal') purse seine fishery (mainly Turkish), and an industrial offshore freezer-trawler fishery. The number of artisanal pirogue purse seiners fluctuates around 350, the coastal purse seiners around 50 and the trawlers around 50. The latter fleet can be divided into two categories: Russian-type trawlers, which have been present in the area since 1970 and whose strategy is oriented towards Carangidae, and Dutch-type trawlers, which arrived in 1996 and whose strategy is oriented towards Clupeidae. The Dutch trawlers constitute the largest units in the industrial fleet in terms of length, tonnage and engine power (Braham, 2013).

In relation to the neighboring countries who share these stocks to a greater or lesser extent: In Morocco, sardinella are mainly by-catch in the fishery targeting other small pelagic species such as sardine, mackerel and horse mackerel (Corten et al., 2012). These catches involve coastal purse seiners, RSW (Refrigerated Sea Water) trawlers and freezer trawlers. In Senegal, sardinella are fished both by purse seine, which is the main gear, and gillnets which are used mainly to target flat sardinella. These gears are used by artisanal pirogues ranging in length from 12 to 15 m for those using gillnets and up to 20 m for those using purse seines. The purse seines range in length from 200 to 400 m. In 2018 there were estimated to be 12,000 active pirogues (Gouvernement de Sénégal, 2019). In The Gambia, the fishing gears used to catch sardinella are purse seine, encircling gillnets and semi-encircling gillnets (Corten, 2012). These gears are also used aboard traditional pirogues.

The distribution of sub-regional catch of sardinella by country shows the importance of the Senegalese-Mauritanian area for both species, followed by Morocco for round sardinella. Catches of round sardinella are dominated by Mauritania, whereas Senegal catches more flat sardinella, but with Mauritania coming towards parity in recent years (Fig. 2). In recent years 400 Senegalese purse seine pirogues have been authorized to fish in the Mauritanian zone under a fishing agreement between the two countries. Only 20 % of these pirogues are obliged to land their catch in Mauritania, with the rest authorized to land their catch in the Senegalese port of Saint Louis. Hence some of the catch reported as Senegalese likely comes from Mauritanian waters.

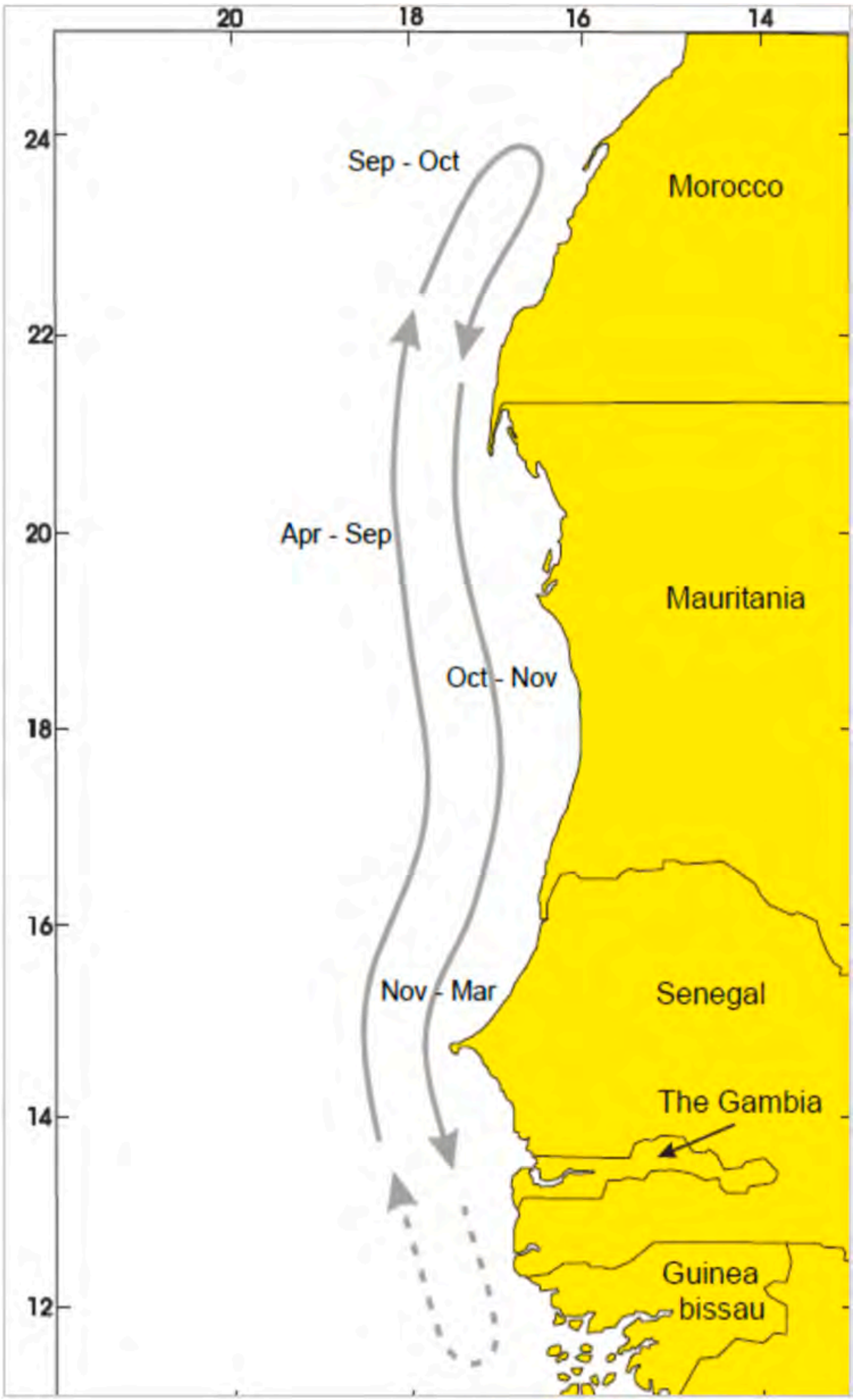

Fig. 1. Migration pattern of the round sardinella (adapted by Corten et al., 2012).

3. Materials and methods

3.1. Data

The analysis was based on combined commercial catch data for the period 1995–2021. We use size-frequency data collected by observers on board vessels and by data collecters at landing sites and freezing and fishmeal plants. The collection of landing and biological sampling data is carried out by investigators and observers from research institutes in the countries of the sub-region (Fig. 3 B):

- National Institute for Fisheries Research (INRH) in Morocco
- Mauritanian Institute of Oceanographic Research and Fisheries (IMROP) in Mauritania
- Dakar-Thiaroye Oceanographic Research Center (CRODT) in Senegal and
- Ministry of Fisheries and Water Resources (MFWR) of The Gambia

During the CECAF working groups held annually under the supervision of the FAO, each country provides data on the quantity fished per species, the intensity of biological sampling (number of individuals measured, biological analyses, coverage rate, etc.), data from scientific surveys and a description of recent developments over the past year. According to FAO criteria, sampling intensity should be at least 1 sample for every 1000 tonnes caught. Sampling intensity has improved since the launch of several research support projects in the sub-region AGD pélagique financed by the MAVA Foundation, Promopêche financed by GIZ, FIP-small pelagic financed by private operators, Shared Sardinella financed by Nansen-FAO.

For round sardinella, the species was targeted by the Dutch offshore fleet working in the Mauritanian zone, which allowed us to generate a standardized CPUE time series for the period 1995–2012 (Corten et al., 2017). Since the withdrawal of these vessels from the zone after the zoning change in 2012, the remaining industrial vessels targeted both horse mackerel and clupeids, making CPUE standardization problematic (Braham et al., 2014). In the Senegalese zone, where the species is fished by Saint Louis-type pirogues, the standardization of commercial CPUE was also not possible due to the lack of operational data (use of several gears, lack of information on vessel charateristics; Corten et al., 2012).

Therefore, we also used abundance indices from acoustic surveys that cover the distribution area of two stocks. These surveys for the vessel Nansen are carried out during the same period at the end of the year from October to December and cover the entire distribution area of these species. The surveys were carried out continuously from 1995 to 2006, with a break between 2007 and 2014. They resumed in 2015, 2017 and 2019 to ensure coverage of the area. There were also national surveys, limited to each portion of the stock distribution, but these have been irregular in the area of abundant sardinella stocks, especially in the Senegal-Mauritania zone.

During the Nansen sub-regional surveys, acoustic data were collected day and night. The sampling scheme followed transects oriented perpendicular to the coast from depths greater than 10 m and up to 500 m. Radials were 10 nautical miles (nmi) apart. R.V. Fridtjof Nansen examined about 7000 nautical miles of transects in total (Fig. 3 A).

Details on the Nansen surveys can be found in the corresponding FAO reports (e.g. FAO, 1999; www.fao.org/corp). This international surveys

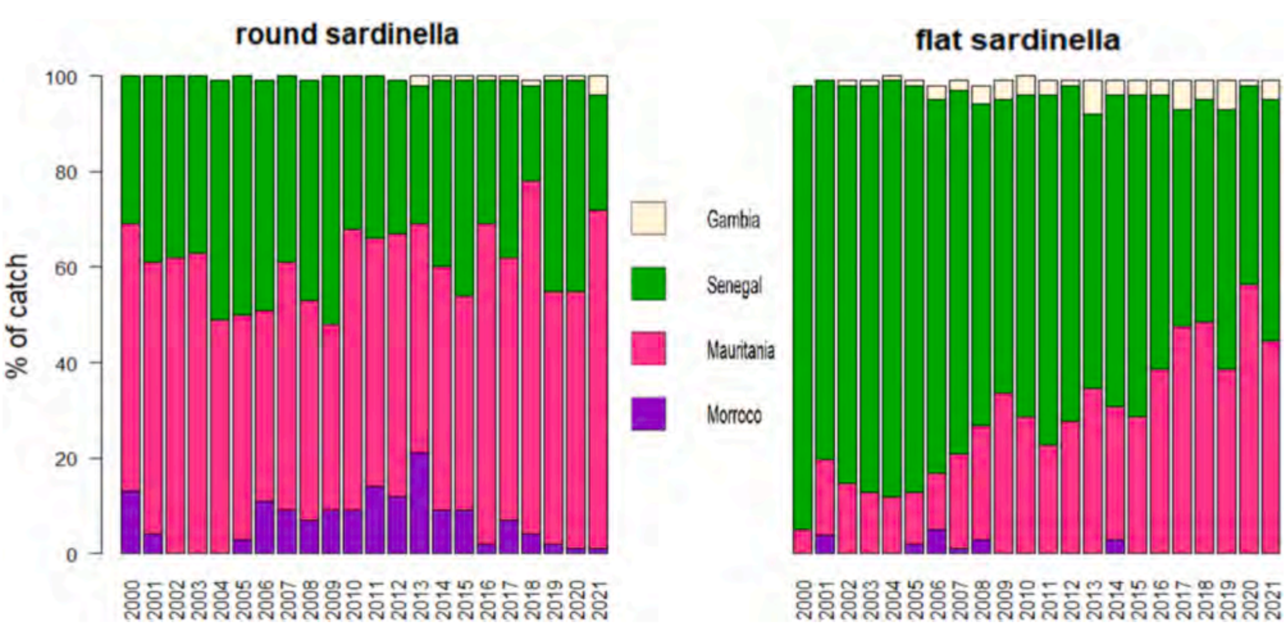

Fig. 2. Percentage of total landings of the two species of sardinella by country (WG-CECAF-2021 data).

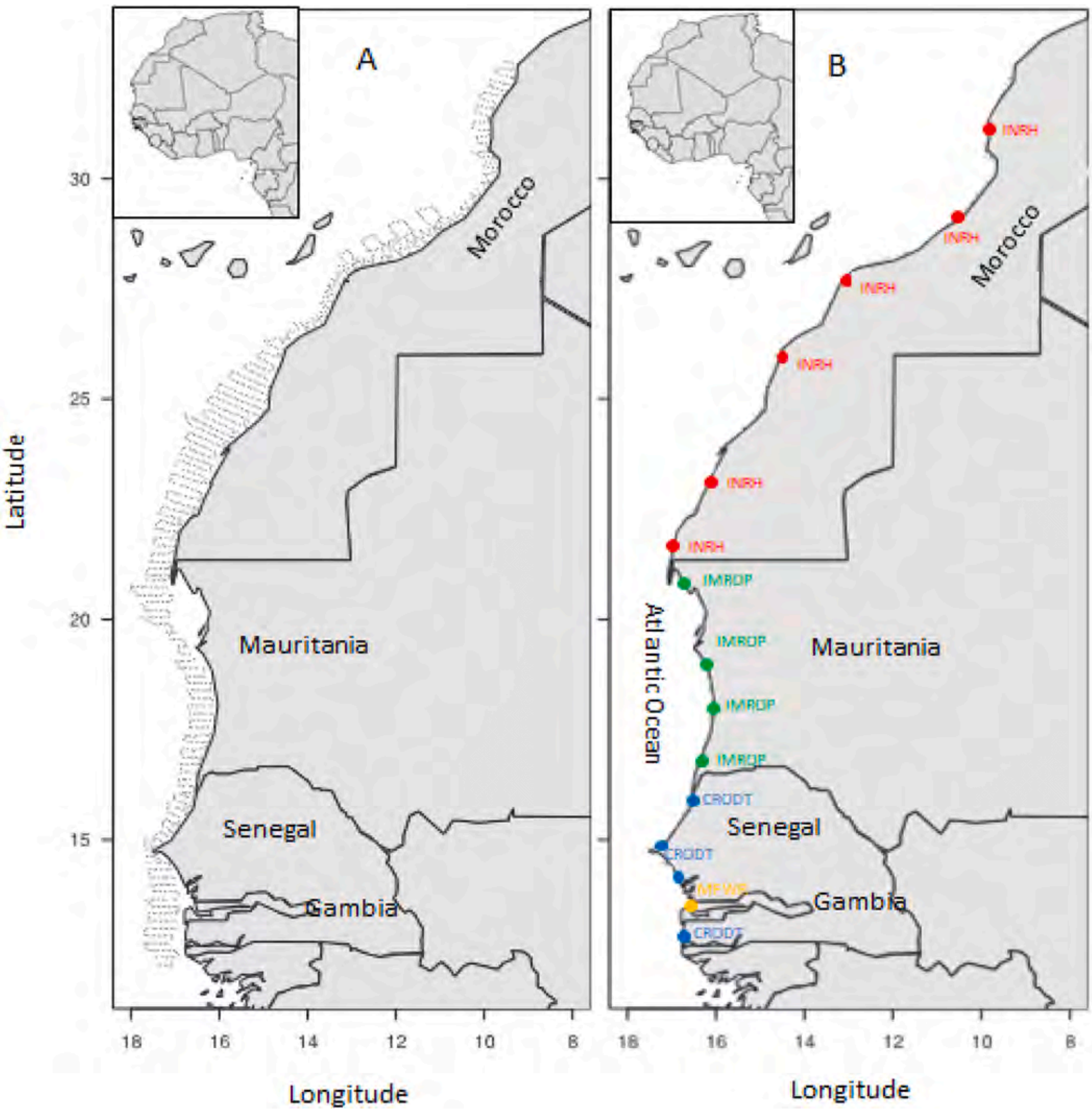

Fig. 3. Map showing the trajectory of acoustic surveys carried out by the research vessel Fridjoft Nansen (A) and the main landing points monitored by surveyors and observers from the sub-region's research institutes on the distribution scale of sardinella stocks (B).

were conducted with the same acoustic material (Simrad EK-500, dual-frequency 38 kHz and 120 kHz, threshold for filtering the echoes of −70 dB) calibrated by the standard sphere method (Foote et al., 1987) and the same elementary sampling distance unit (ESDU) equal to five nautical miles. During these surveys, the objective was to identify the acoustic echoes at the species level whenever possible (MacLennan and Simmonds, 1992; Reid, 2000) using the Bergen Integrator (BEI; Knudsen, 1990). Where it was not possible to be that detailed, the energy was allocated to a wider group based on a combination of a visual scrutiny of the behavior pattern as deduced from echo diagrams and the catch compositions.

3.2. *Selection of models*

In order to choose the models best suited to the situation of the sardinella fishery, given the lack of standardized and homogeneous data, it was deemed appropriate to use the FishPath tool to guide this reflection (https://tool.fishpath.org/home).

The FishPath tool is a web-based decision support tool for the management of data-constrained fisheries. The main objective of the FishPath tool is to help users understand and refine options for the three main components of a harvest strategy:

- Data collection
- Data-limited assessment and

Table 1
Summary of selected results fishery: sardinella fishery CECAF North (FishPath).

Option	Assessment Category	Assessment Output	Meets Criteria	Red Caveats	Orange Caveats	Yellow Caveats	Positive Attributes	Static Caveats
Extended Simple Stock Synthesis (XSSS)	Population Dynamics Model	Catch Limit, Fishing Rate, Stock Scale, Stock Status	Yes (10/10)	4	1	4	1	2
Production model	Population Dynamics Model	Catch Limit, Stock Scale, Stock Status	Yes (3/3)	2	2	5	0	7
Catch-MSY/CMSY	Catch Only	Catch Limit	Yes (3/3)	3	3	2	0	4
Length-based Bayesian Biomass Estimation (LBB)	Size/Age-Based	Stock Status	Yes (4/4)	2	0	6	0	4

Table 2
Inputs of the models used according to the information available on the priority and the choice of the model.

Species	Method	Time series	Inputs
Round sardinella (*Sardinella aurita*)	JABBA	1995–2021	Catch 1995–2021, acoustic abundance index, models (Fox, Pella and Schaefer), specify initial depletion prior Bo/K (psi.prior) between 0.2 and 1 for initial depletion
	LBB	2016–2021	Catch and length-frequencies 2016–2021; Linf prior 380 mm TL; L50 prior 180 mm TL
Flat sardinella (*S. maderensis*)	JABBA	1995–2021	Catch 1995–2021, acoustic abundance index, models (Fox, Pella and Schaefer), psi.prior between 0.2 and 1 for initial depletion
	LBB	2017–2021	Catch and length frequencies 2017–2021; Linf prior 380 mm TL; L50 prior 180 mm TL

- Management actions

In this case, it was being used to select appropriate assessment methods for the available data.

The FishPath tool uses multiple-choice questions, covering social, economic, operational, biological, ecological and governance characteristics, and the types of data available. The FishPath tool contains a database of approximately 50 options for each of the 3 sections (data collection, assessment, management measures). Responses to the questionnaire indicate the key assumptions, considerations and caveats for each option contained in the FishPath tool. The results section of the tool provides a guided process for narrowing down the available options to a shortlist to be more formally considered.

Note that the FishPath tool is not a stock assessment or simulation tool (Dowling et al., 2022). It helps to identify a short list of viable options, but it does not prescribe a single preferred option.

The Shared Sardinella project (http://www.fao.org/in-action/eaf-nansen/en) carried out an online meeting in April 2022 to complete the FishPath criteria for the combined sardinella stock. All participants therefore jointly answered the questions posed within the 3 components: 1) data collection, 2) assessment and 3) management measures.

After answering the 40 questions on stock assessment, the group evaluated the proposals made by FishPath on the possible options for an assessment method for sardinella (https://tool.fishpath.org/questionnaire/results/ccbf8e30-d130–447d-950e-2bdf1c37f8e8/monitoring) (Table 1).

In other words, the tool proposed that four models could be investigated to evaluate their compatibility with the data currently available:

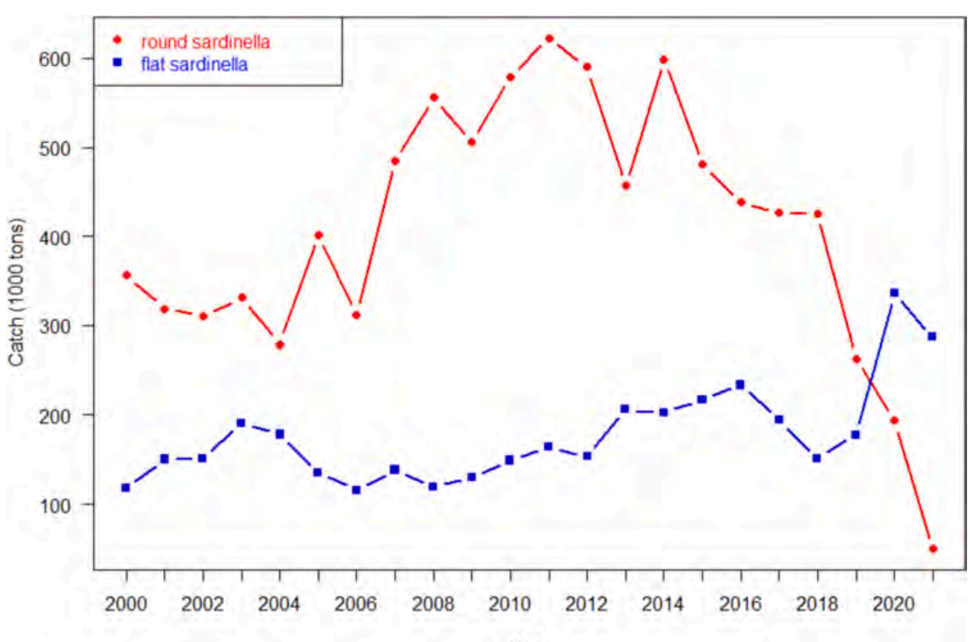

Fig. 4. Time series of regional catch of the two species (thousand tons) (COPACE, 2022).

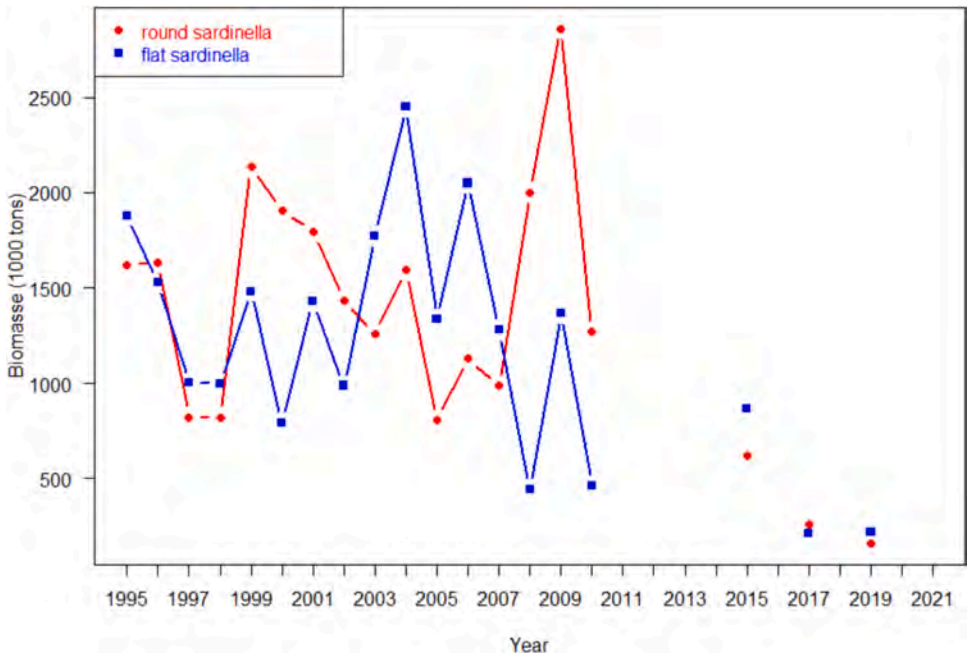

Fig. 5. Trends in the biomass of sardinella estimated by different research vessels (Dr. Fridtjof Nansen and national vessels) (thousand tons).

Table 3
Summary of posterior quantiles presented in the form of marginal posterior medians and associated the 95 % credibility intervals (5 % LCI and 95 % UCI) of parameters for the reference case JABBA model (Schaefer) for North West africa sardinella.

	Round sardinella			Flat sardinella		
	Median	LCI	UCI	Median	LCI	UCI
K	7794,705	4,499,958	14,517,479	2,508,556	972,033	4,884,116
r	0.117	0.028	0.352	0.180	0.033	0.751
Initial depletion	0.90	0.75	1.09	0.90	0.75	1.0921195
Sigma.proc	0.105	0.028	0.199	0.097	0.03	0.198
m	2	2	2	2	2	2
FMSY	0.058	0.014	0.176	0.09	0.017	0.375
BMSY	3897,352	2,249,979	7,258,739	1,254,278	486,016	2,442,057.82
MSY	233,850	72,110	470,400	114,392	31,282	263,036.125
BMSY/K	0.5	0.5	0.5	0.5	0.5	0.5
B1995/K	0.902	0.68	1.152	0.908	0.682	1.182
B2021/K	0.045	0.021	0.116	0.127	0.024	0.602
B2021/BMSY	0.09	0.041	0.232	0.254	0.047	1.205
F2021/FMSY	2.465	0.634	9.98	11.76	1.005	79.87

- Extended Simple Stock Synthesis (XSSS)
- Catch MSY/CMSY
- JABBA-Select Tool (Production model)

- LBB (Length-Based Bayesian Biomass Estimation)

After some communication with Stock Synthesis experts (Kelli Faye Johnson, Northwest Fisheries Science Center, pers. comm.), it was concluded the outputs from this type of model would not be robust without some age data, and it was decided to adopt this as a longer-term project. The Cmsy method is not well adapted for an evaluation of stock status, because this is a prior input, although it could be subsequently used in a consideration of appropriate catch limits, given better information on stock status (which is the objective here). Other recent works show that there are also strong criticisms of Cmsy (Ovando et al., 2022). The group therefore decided that the most appropriate approach would be to apply the two production models: JABBA and LBB. The current preferred method for surplus production models is to formulate them as Bayesian models, which allows the use of a range of different sources of information about the stock to help estimate parameters and reduce uncertainties in the results. This approach can also help to incorporate process and observation errors into the model (Winker et al., 2018; Winker et al., 2020).

The JABBA model was applied using acoustic-derived abundance indices for two species. The LBB model was applied for both species using size data, since collection and coverage of these data has improved in the area with the support of some sub-regional projects.

3.3. Description of the JABBA method

The JABBA model provides a generalized Bayesian state-space estimation framework for surplus production models (SPMs) by building on previous formulations by Pella and Tomlinson (1969), Gilbert (1992); (Wang et al., 2014) and Fletcher (1978); (Thorson et al., 2012). The Surplus Production (SP) function is formulated with the generalized three parameter SPM by Pella and Tomlinson (1969) of the form:

$$SP_t = \frac{r}{m-1} \quad B_t \quad \left(1 - \left(\frac{B_t}{K}\right)^{m-1}\right) \tag{1}$$

where r is the intrinsic rate of population increase at time t, K is the carrying capacity, B_t is stock biomass at time t, and m is a shape

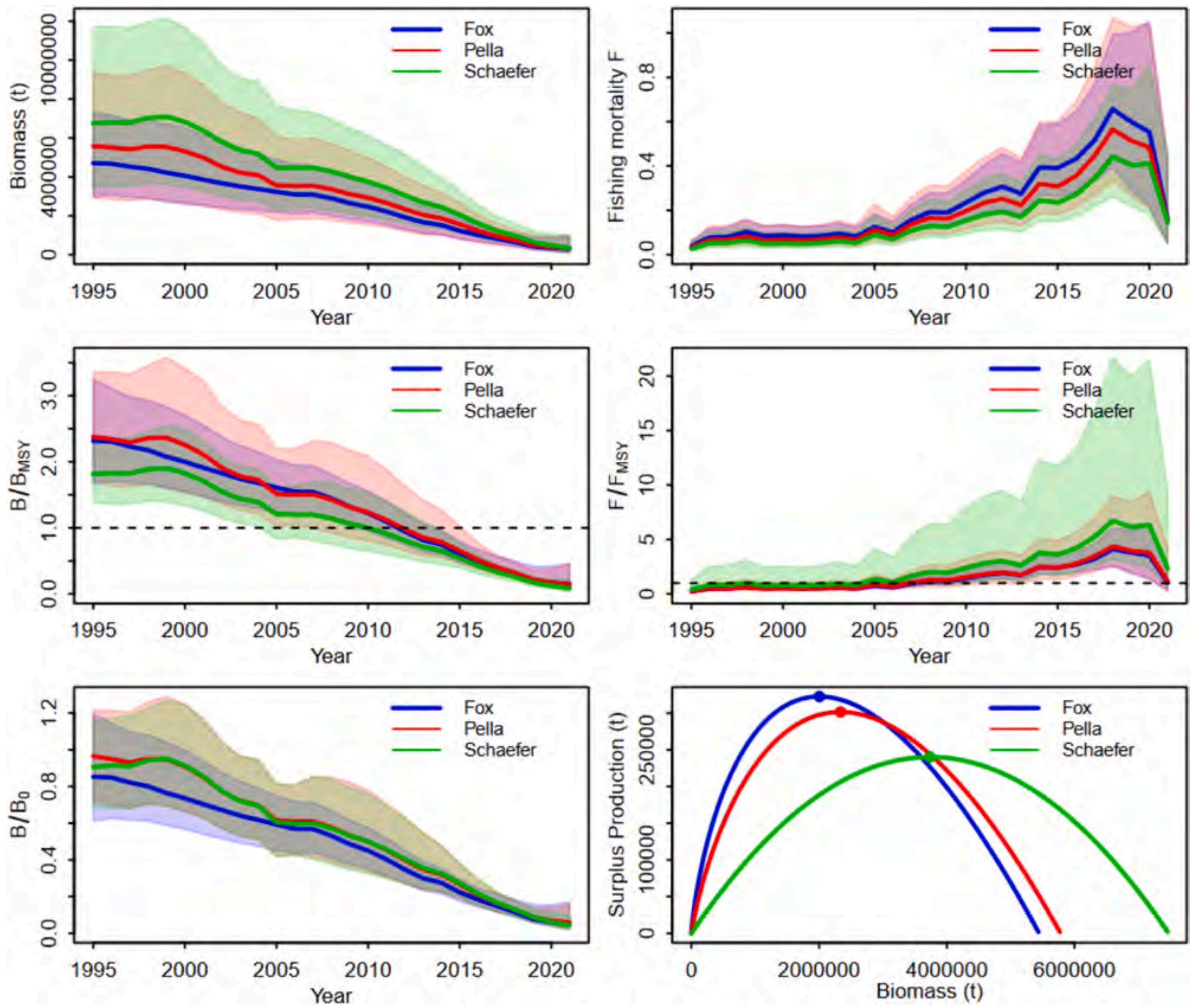

Fig. 6. Analysis performed on the differents models applied to round sardinella and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to BMSY (B/BMSY) and fishing mortality relative to FMSY (F/FMSY) (middle panels) and biomass relative to K (B/K) and surplus production curve (bottom panels) for each scenario from the model.

parameter that determines at which B/K ratio maximum surplus production is attained. If the shape parameter m = 2, the model reduces to the Schaefer form, with the surplus production (SP) attaining the Maximum Sustainable Yield (MSY) at K/2. If $0 < m < 2$, SP attains MSY at biomass levels smaller than K/2; the converse applies for values of m greater than 2. The Pella Tomlinson model reduces to a Fox model (Fox, 1970) as m approaches one, resulting in maximum surplus production at ~ 0.37 K, but there is no solution for the exact Fox surplus production with m = 1. The shape parameter m can be directly translated into the biomass level where MSY is achieved, B_{MSY}, via the ratio B_{MSY}/K:

$$\frac{B_{MSY}}{K} = m\left(-\frac{1}{m-1}\right) \tag{2}$$

It follows that B_{MSY} is given by:

$$B_{MSY} = Km\frac{-1}{m-1} \tag{3}$$

It follows that F_{MSY} is given by:

$$F_{MSY} = \frac{r}{m-1}\left(1-\frac{1}{m}\right) \tag{4}$$

where the fishing mortality is an annual rate defined here as the ratio of:

$$F = \frac{C}{B} \tag{5}$$

where C denotes catch (=MSY at F_{MSY}). Correspondingly, MSY can be expressed by:

$$MSY = F_{MSY}B_{MSY} \tag{6}$$

We note that the Pella-Tomlinson formulation provides an approximate link to an age-structured model. Combining and re-arranging Eqs. (3), (4), and (6), it follows that r in Eq. (1) can be expressed as:

$$r = \frac{MSY}{B_{MSY}}\frac{m-1}{1-m^{-1}} \tag{7}$$

Eq. (2) together with the re-rearranged Eq. (7) emphasizes the potential of translating estimates of MSY/B_{MSY} and B_{MSY}/K into r and m, respectively (Maunder, 2003; Thorson et al., 2012; Wang et al., 2014). This presents a crucial bridge for parameters derived from age-structured equilibrium models (e.g., a per-recruit analysis with integrated Beverton-Holt recruitment functions) to be implemented in an SPM.

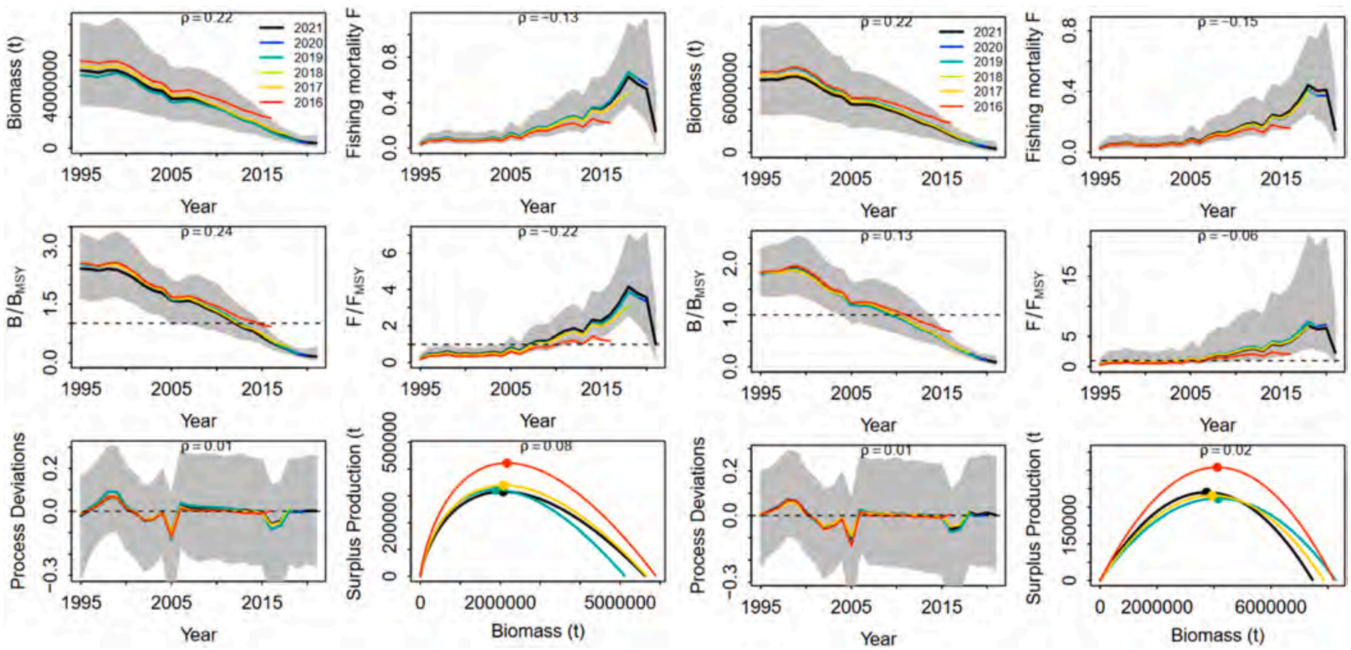

Fig. 7. Retrospective analysis performed on the Schaefer (left) and Fox (right) models, by removing one year at a time sequentially (n = 5) and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to BMSY (B/BMSY) and fishing mortality relative to FMSY (F/FMSY) (middle panels) and biomass relative to K (B/K) and surplus production curve (bottom panels) for each scenario from the model fits to the round sardinella.

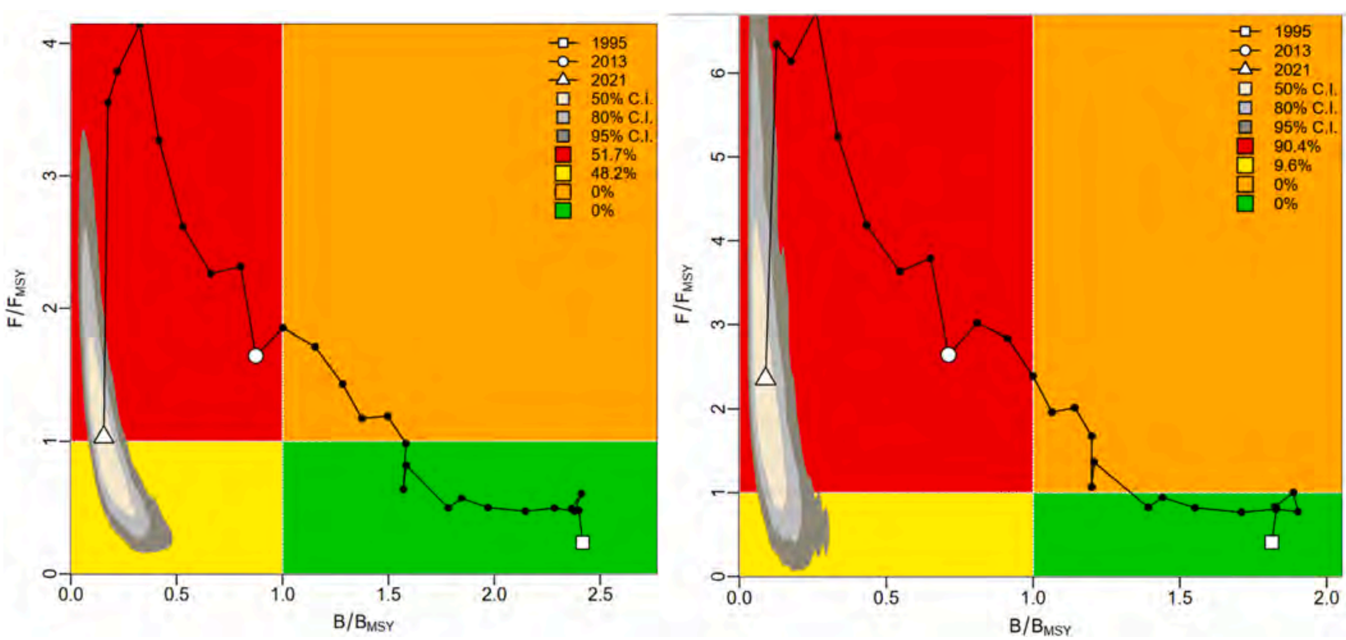

Fig. 8. JABBA surplus production phase plot for the Schaefer model (left) and Fox model (right) for round sardinella showing trajectories of the catches in relation to BMSY and MSY (top panel) and Kobe phase plot showing estimated trajectories (1995–2021) of B/BMSY and F/FMSY for the Bayesian state-space surplus production model for the round sardinella (bottom panel). Different gray shaded areas denote the 50 %, 80 %, and 95 % credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

3.4. Description of the length-based Bayesian biomass (LBB) method

The new LBB estimator approach is a powerful method which is used for estimating the stock status by analyzing length-frequency data from the exploited fishery (Froese et al., 2018; Wang et al., 2020). This method works for species which grow throughout their lives, as generally most of the commercially valuable fishes and invertebrates do, where only the length-frequency data are required as input. Approximation of various parameters from length-frequency data by this method represents the population in question, together with the asymptotic length (Linf), length at first capture (Lc), relative natural mortality (M/K) and relative fishing mortality (F/M) (Froese et al., 2018, 2019). Only the basic formulas have been presented here; for complete information, see (Froese et al., 2018). It is assumed in the LBB method that the increase in length follows the Von Bertalanffy (1938) growth equation in the form given by Beverton and Holt (1957), that is:

$$Lt = Linf\ [1 - e^{-k(t-t0)}] \quad (1)$$

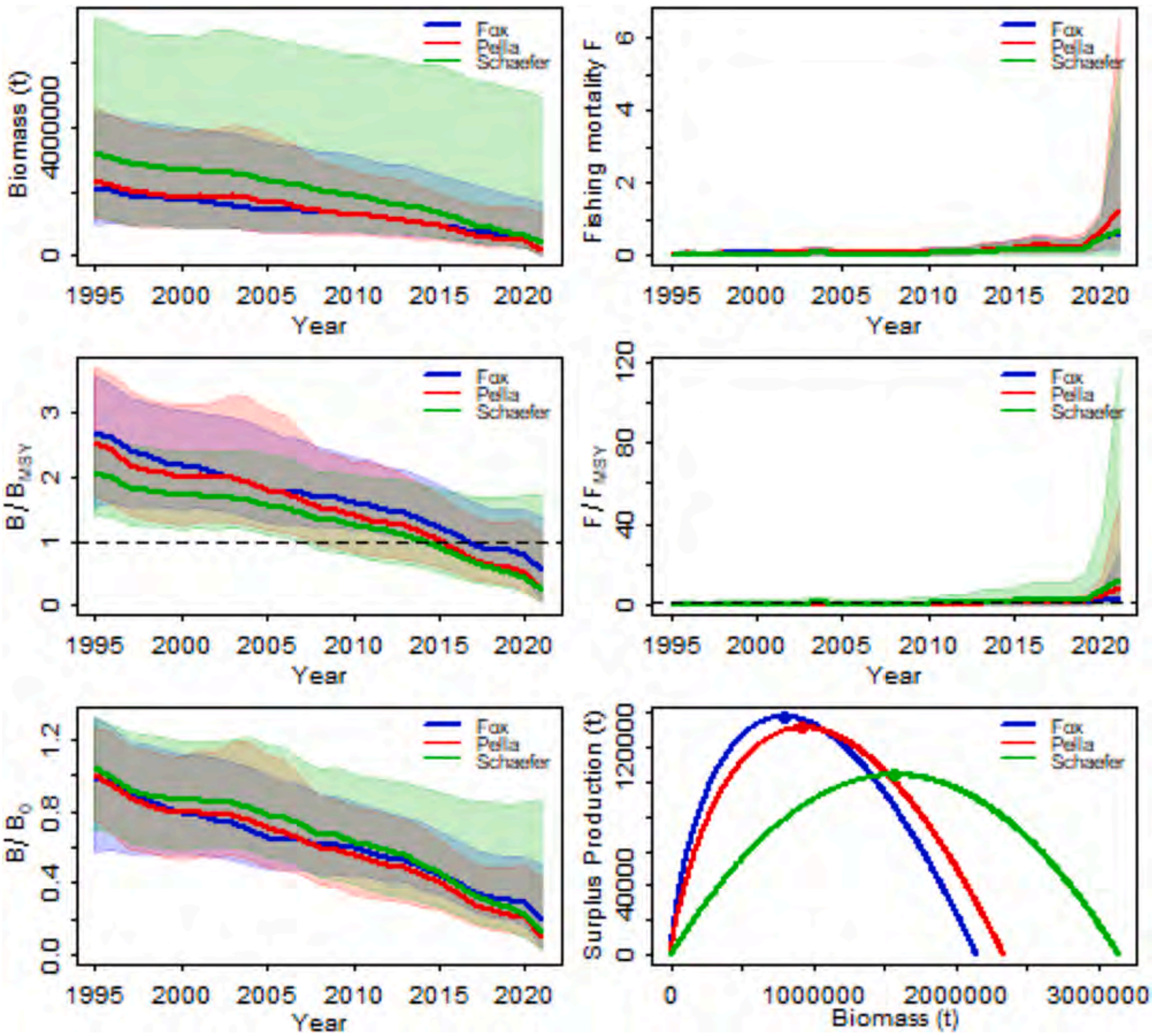

Fig. 9. Analysis performed on the differents models applied to flat sardinella and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to BMSY (B/BMSY) and fishing mortality relative to FMSY (F/FMSY) (middle panels) and biomass relative to K (B/K) and surplus production curve (bottom panels) for each scenario from the model.

where Lt denotes length at age t, Linf is asymptotic length, k is the growth coefficient, and t0 indicates the theoretical age of fish at zero (0) length (Froese et al., 2018). When the fish become fully selected to the gear, the total mortality (Z = M + F) function which, relative to the growth coefficient (k) is indicated by the right-hand side of the curve in the length-frequency samples, can be expressed by the Eq. (2):

$$N_l = N_{Lstart}\left(\frac{L_{\inf} - \mathrm{L}}{L_{\inf} - L_{start}}\right)\mathrm{Z}\Big/\mathrm{K} \tag{2}$$

where N_L indicates the number of survivors at length L and N_{Lstart} shows the number at length Lstart with full selection, from which all individuals entering the gear are retained by the gear. Usually, the fishing gears have typical selection curves; in this LBB, trawl-type selection was assumed, i.e., very young individuals escaping capture (L<Lstart). This type of selectivity was also considered appropriate for the other main gear type (purse seine) which tends to be unselective except at small size. This type of selectivity of the gear can be explained as follows by Eq. (3):

$$S_l = \frac{1}{\left[1 + e^{-\propto(L - Lc)}\right]} \tag{3}$$

where SL indicates the fraction of individuals at the length L that are retained by the gear, and alpha (α) is the steepness of the ogive, which describes the length-based selectivity of the gear (Froese et al., 2018). The parameters of the selection ogive are estimated at the same time as Lc, α, M/K, and F/K by fitting

$$N_l = N_{Li-1}\left(\frac{L_{\inf} - L_i}{L_{\inf} - L_{i-1}}\right)^{\frac{M}{k} + \frac{F}{k}S_{Li}} \tag{4}$$

and,

$$C_{Li} = N_{Li} \quad S_{Li} \tag{5}$$

where Li refers to the number of individuals at the length i, $L_{i\text{-}1}$ is the number at the previous length, C is the number of individuals who are vulnerable to the gear, and all other parameters are as previously mentioned Froese et al. (2018). Finally, the equation below explains the

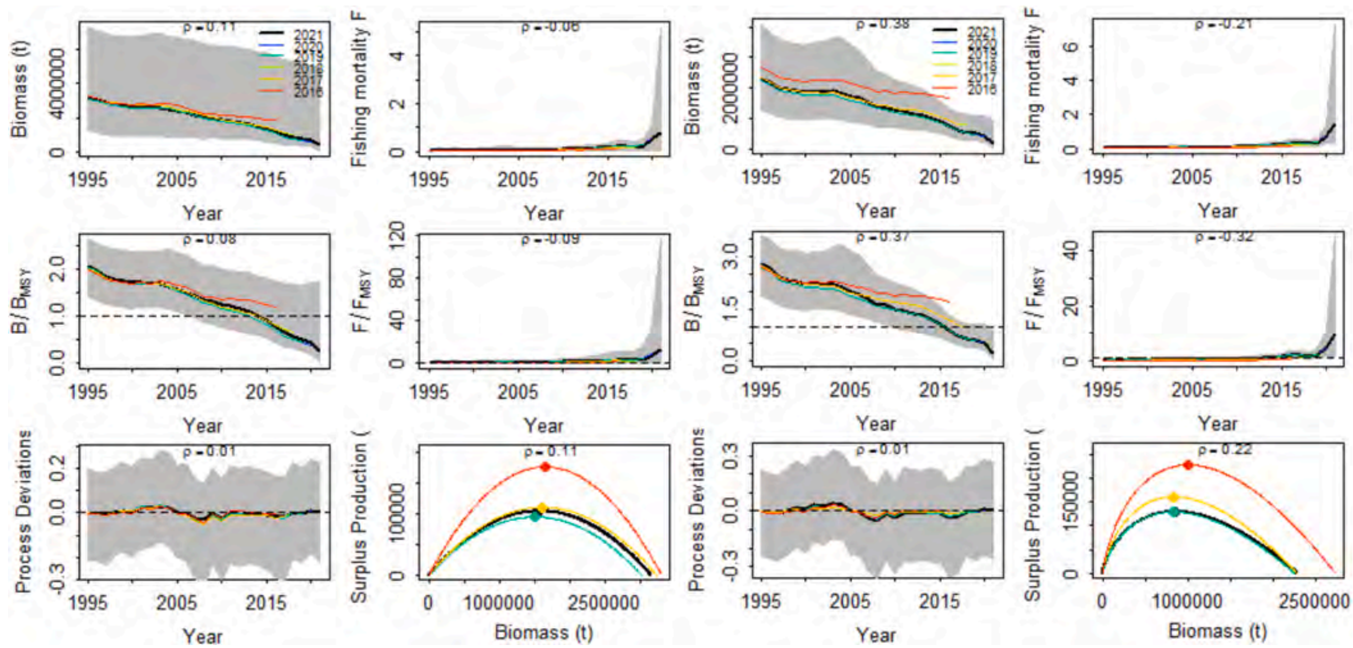

Fig. 10. Retrospective analysis performed on the Schaefer (left) and Fox (right) models, by removing one year at a time sequentially (n = 5) and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to BMSY (B/BMSY) and fishing mortality relative to FMSY (F/FMSY) (middle panels) and biomass relative to K (B/K) and surplus production curve (bottom panels) for each scenario from the model fits to the flat sardinella.

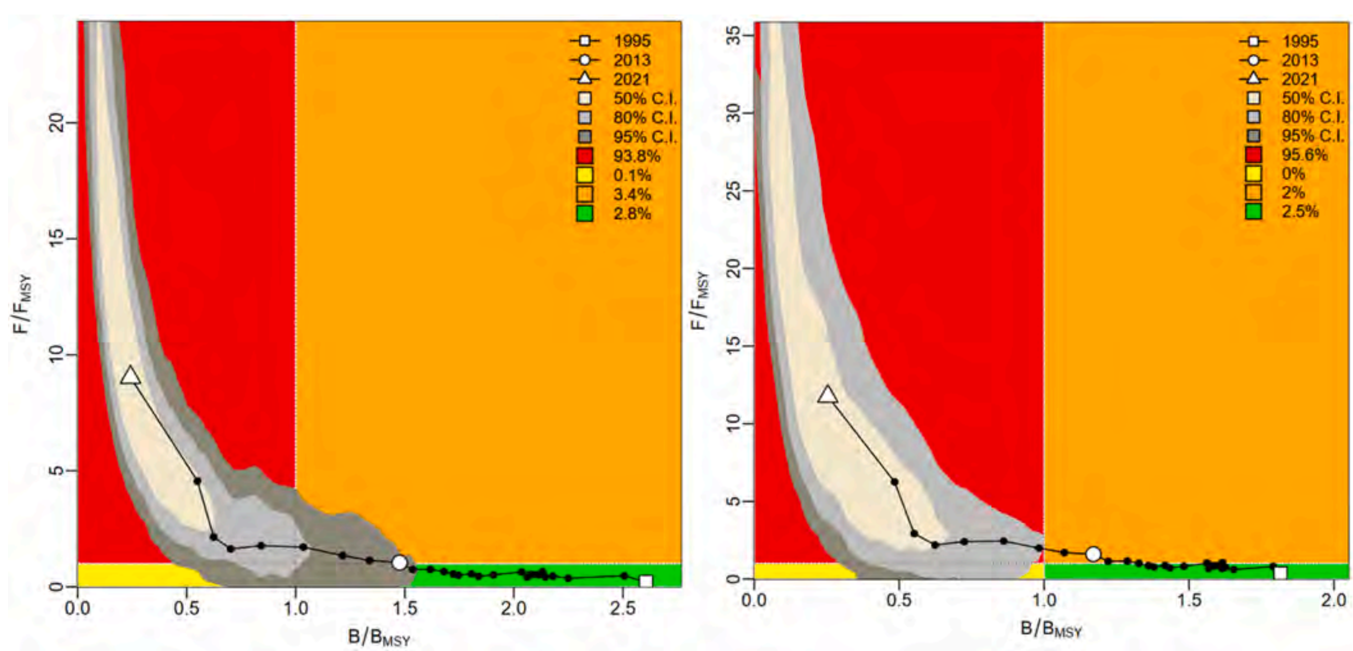

Fig. 11. JABBA surplus production phase plot for the Fox model (right) and Schaefer model (left) for flat sardinella showing trajectories of the catches in relation to BMSY and MSY (top panel) and Kobe phase plot showing estimated trajectories (1995–2021) of B/BMSY and F/FMSY for the Bayesian state-space surplus production model for the round sardinella (bottom panel). Different gray shaded areas denote the 50 %, 80 %, and 95 % credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

framework for the approximation of stock status from Linf, F/k, M/k, and Lc [Froese et al., 2017]. At first, given the Linf estimation and M/k, Lopt, i.e., the size of fish at which cohort biomass is at the maximum, can be estimated from Eq. (6) below:

$$L_{opt} = L_{\inf} \quad \left(\frac{3}{3+\frac{M}{k}}\right) \tag{6}$$

The mean length at first capture, which makes a maximum catch and biomass (Lc_opt), can be obtained from the following equation, based on Eq. (6) and the given fishing pressure (F/M):

$$L_{c-opt} = \frac{L_{\inf} \quad (2+3\frac{F}{M})}{1+\frac{F}{M})(3+\frac{M}{k})} \tag{7}$$

The Lc_opt estimations are used below for calculating a proxy for the relative biomass, which can produce the MSY (Froese et al., 2018).

An index of yield-per-recruit (Beverton and Holt, 1966) can be expressed as a function of Lc/Linf, F/K, M/K, and relative fishing mortality F/M:

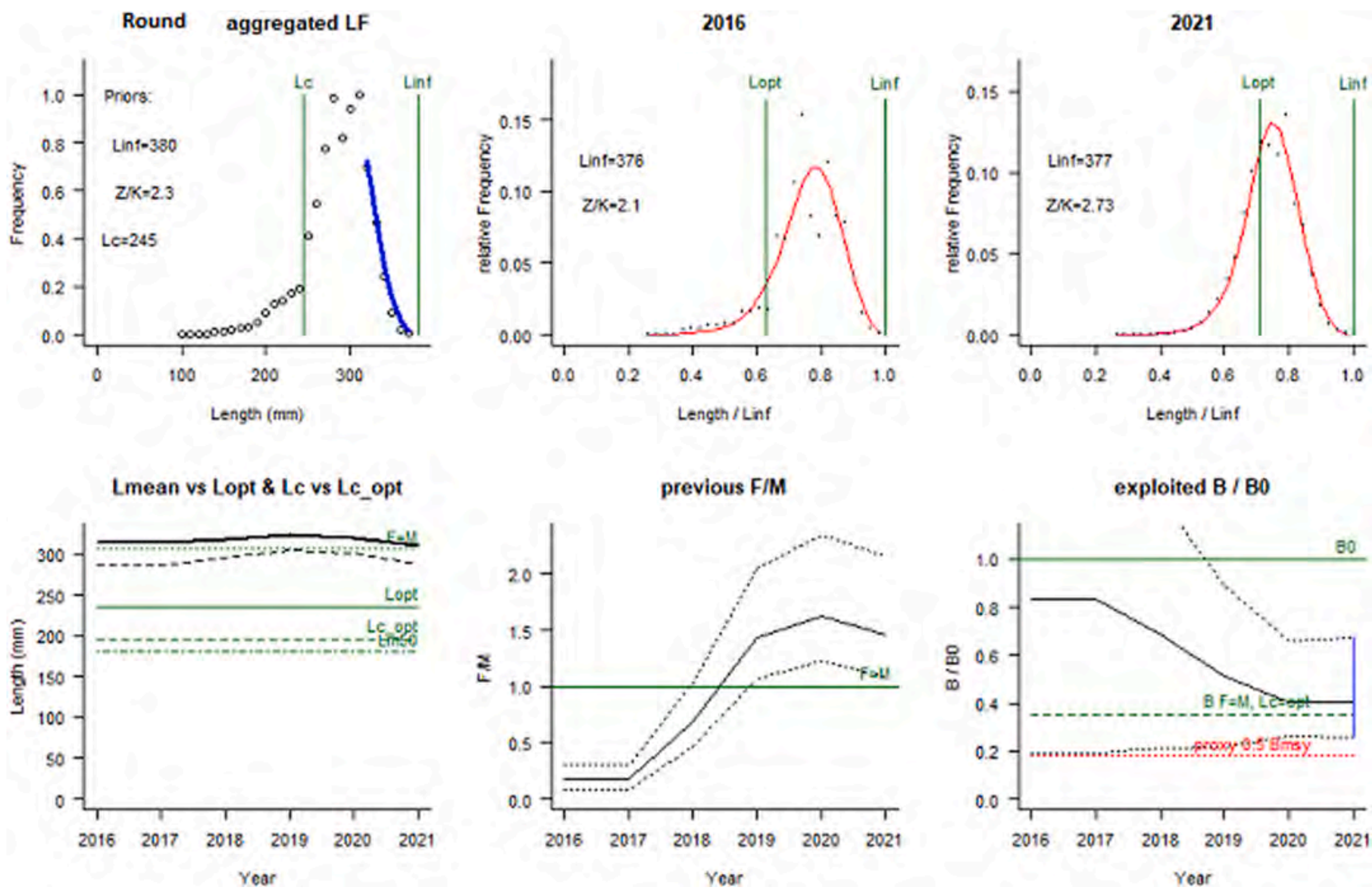

Fig. 12. Results of the LBB for round sardinella. Top-left: aggregated length frequency (LF) data and priors for Lc, Linf, and Z/k. Top-mid and top-right: dots are the length-frequency data for the first and last years, and the red line is the fit of the data to the LBB master equation, for 2016 and 2021 respectively. Bottom-left: mean length (Lmean, bold black curve) relative to Lopt, and Lc (dashed black curve) relative to Lc_opt. Bottom mid: relative fishing mortality F/M (black curve), with approximate 95 % confidence limits (dotted lines), and reference level (F = M, green horizontal line). Bottom right: relative biomass B/B0 (black curve) with approximate 95 % confidence limits (dotted black curves), and a proxy for BMSY (green dashed line), and a proxy for Bpa or 0.5 BMSY (red dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\frac{Y'}{R}=\frac{F/M}{1+F/M}\left(1-L_c/L_{\inf}\right)^{M/K}\left(1-\frac{3\left(1-L_c/L_{\inf}\right)}{1+\frac{1}{M/K+F/K}}+\frac{3\left(1-L_c/L_{\inf}\right)^2}{1+\frac{2}{M/K+F/K}}-\frac{\left(1-L_c/L_{\inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \tag{8}$$

An index of catch per unit of effort (CPUE'/R) is obtained by dividing Eq. (8) by the fishing intensity F/M, assuming that fishing mortality F is directly proportional to fishing effort. Since CPUE is proportional to biomass in the exploited phase of the stock, Eq. (10) represents relative CPUE'/R as well as an index of exploited biomass per recruit B'/R (Beverton and Holt, 1966):

$$\frac{CPUE'}{R}=\frac{Y'/R}{F/M}=\frac{1}{1+F/M}\left(1-L_c/L_{\inf}\right)^{M/K}\left(1-\frac{3\left(1-L_c/L_{\inf}\right)}{1+\frac{1}{M/K+F/K}}+\frac{3\left(1-L_c/L_{\inf}\right)^2}{1+\frac{2}{M/K+F/K}}-\frac{\left(1-L_c/L_{\inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \tag{9}$$

The relative biomass in the exploited phase of the population if no fishing takes place is given by:

$$\frac{B_0' > L_c}{R}=\left(1-L_c/L_{\inf}\right)^{\frac{M}{K}}\left(1-\frac{3\left(1-L_c/L_{\inf}\right)}{1+\frac{1}{M/K}}+\frac{3\left(1-L_c/L_{\inf}\right)^2}{1+\frac{2}{M/K}}-\frac{\left(1-L_c/L_{\inf}\right)^3}{1+\frac{3}{M/K}}\right) \tag{10}$$

where $B_0' > L_c$ denotes the exploitable fraction ($> L_c$) of the unfished biomass (B_0). An index of relative biomass depletion for the exploited part of the population B/B_0 is then obtained from (Beverton and Holt, 1966):

$$\frac{B}{B_0}=\frac{\frac{CPUE'}{R}}{\frac{B_0'>L_c}{R}} \tag{11}$$

A proxy for the relative biomass that can produce MSY (B_{msy}/B_0) was obtained by re-running Eqs. (8–11) with $F/M = 1$ and $L_c = L_{c\_opt}$.

The relative biomass and the length at first capture estimated by LBB can then be used directly for management of data-poor stocks: if relative stock size B/B0 is smaller than BMSY/B0, catches should be reduced; if, on the other hand, the mean length at first capture Lc is smaller than Lc_opt, fishing should start at larger sizes. The method was implemented

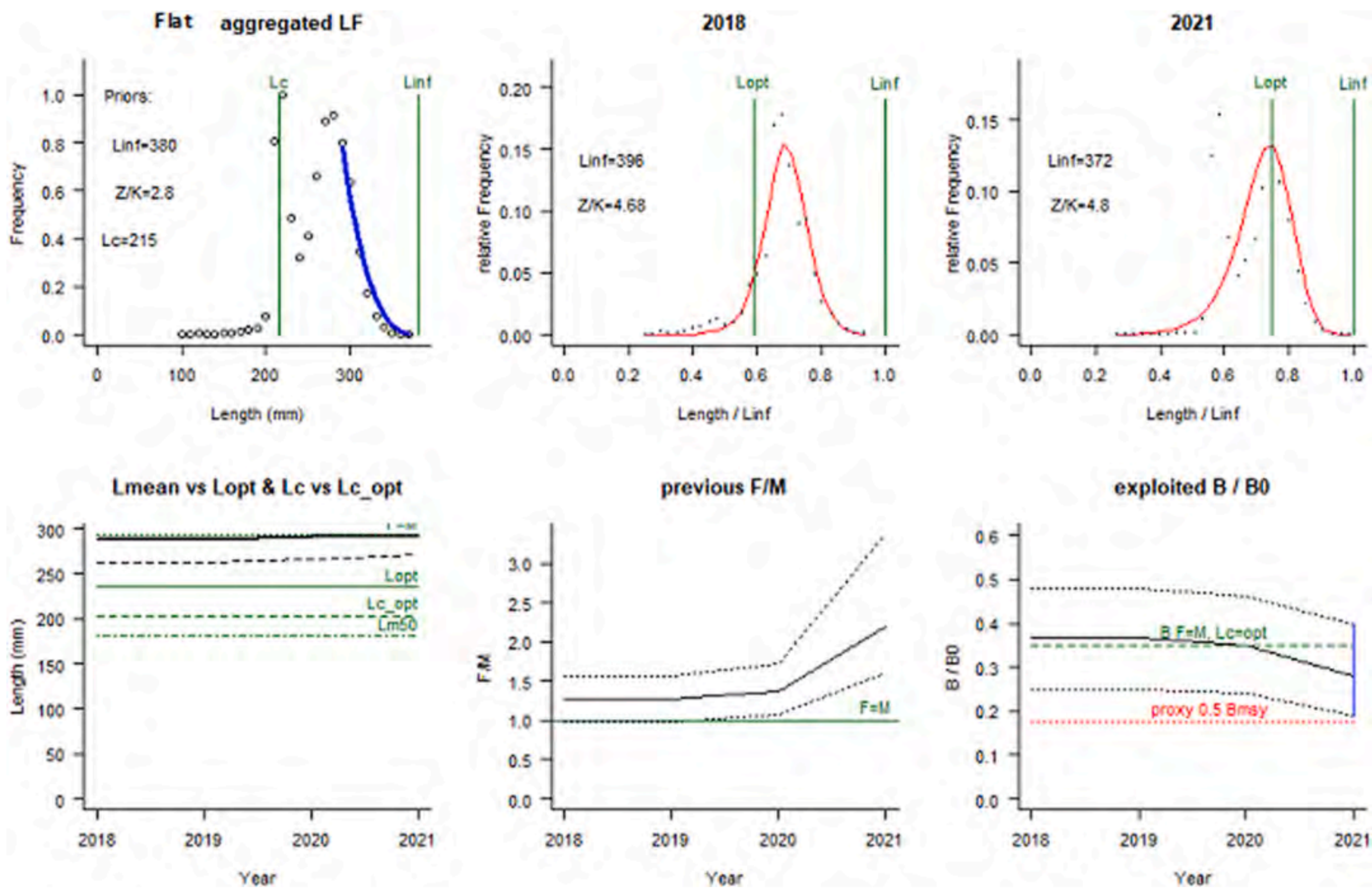

Fig. 13. Top-left: aggregated length frequency (LF) data and priors for Lc, Linf, and Z/k. Top-mid and top-right: dots are the length-frequency data for the first and last years, and the red line is the fit of the data to the LBB master equation, for 2018 and 2021 respectively. Bottom-left: mean length (Lmean, bold black curve) relative to Lopt, and Lc (dashed black curve) relative to Lc_opt. Bottom mid: relative fishing mortality F/M (black curve), with approximate 95 % confidence limits (dotted lines), and reference level (F = M, green horizontal line). Bottom right: relative biomass B/B0 (black curve) with approximate 95 % confidence limits (dotted black curves), and a proxy for BMSY (green dashed line), and a proxy for Bpa or 0.5 BMSY (red dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
summary results of differents models for both species.

	Round sardinella		Flat sardinella	
	JABBA	LBB	JABBA	LBB
B/B0	0.05	0.4	0.18	0.28
B/Bmsy (or proxy)	0.09	~1.2	0.25	~0.8
F/Fmsy (or proxy)	2.46	~1.4	11.76	2.2

within the Bayesian Gibbs sampler software JAGS (Plummer, 2003) and executed using the statistical language R (R Core Team, 2020) to fit observed proportions-at-length.

3.5. Summary of model inputs

The inputs to each model are summarized in Table 2.

Posterior and prior distributions for all parameters estimated by JABBA reference models (Fox, Pella and Schaefer) fitted to catch and abundance data for sardinella are presented in the Supplementary Figure.

4. Results

4.1. Trends in catch and acoustic biomass of two species

The trend of catches of the two species in the northwest African area shows a dominance of round sardinella over flat sardinella during the whole period, except for the last three years in which flat sardinella has become the dominant species. A continuous decline in the catch of round sardinella is observed since 2014 with sharp declines since 2018 (Fig. 4). This last year corresponds to the arrival of the efficient semi-industrial purse seiners, working especially in the coastal zone.

The direct assessment of the two species by acoustic surveys has been irregular, but the biomass estimates by the Norwegian vessel Dr. Fridjoft Nansen during the last five years show a low or even zero biomass of sardinella in the last two years. Although these estimates may be representative for round sardinella which is generally found in offshore areas that are accessible to research vessels, the acoustic estimates may underestimate the biomass of flat sardinella which is distributed partly in coastal areas that are too shallow for research vessels to operate in. There was no survey in 2020, but the abundance index estimated during the surveys carried out in 2019 was the lowest value in the entire historical series, for both species. In addition, the times series for all surveys combined across the region shows a strong downward trend (Fig. 5).

4.2. Results of JABBA model

For the application of JABBA for both species using the abundance indices from the Dr Fridjoft Nansen cruises, which covers the whole area during the same period, for the period 1995–2021, priors are placed on key parameters such as the intrinsic rate of population increase r, carrying capacity K and initial biomass depletion at the beginning of the

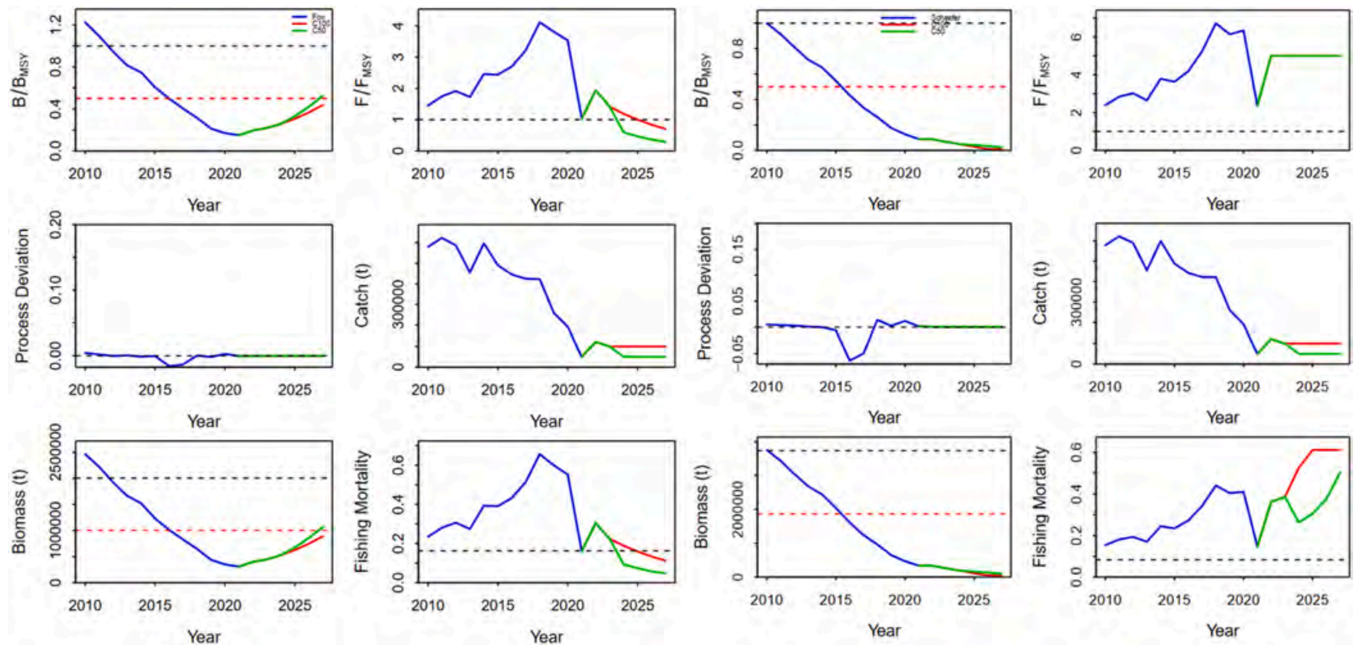

Fig. 14. Simulation of biomass and catch trajectory on the basis of setting a TAC according to the catch of the last year and the average of 3 years for round sardinella.

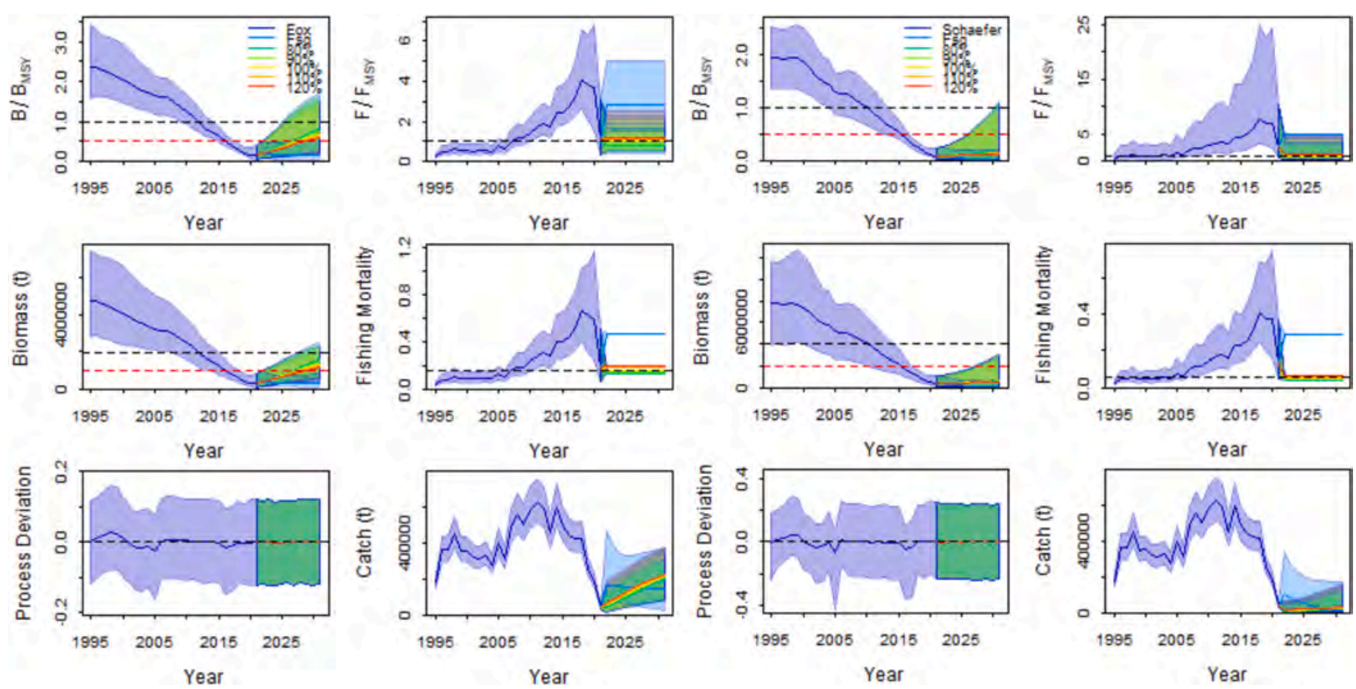

Fig. 15. Simulation of biomass and fishing mortality trajectories based on the Fmsy projection for round sardinella.

available catch time series.

We studied the fit of several production models (Fox, Scheafer, Pella) for the case of two species. For some models, we tried to improve the diagnostics of the series test by modifying the variance parameters by increasing the minimum error of observation from 0.01 to 0.1. In addition, for the case of the Pella model, we tested a scenario by estimating the shape m as a function of $BMSY/K = 0.4$ but this made no significant difference to the model output and was not taken forward. Finally, for the Schaefer case, we compared the catch-only scenario with the one using the abundance index. The summary of the estimated parameters for both species for the Schaefer model case is presented in Table 3. The estimated parameters for the other models are comparable with those for the Schaefer model. It should be noted that a review of the most suitable stock assessment models for fisheries in the North West African zone was carried out under the auspices of the FAO in 2018. Among the most suitable production models for these fisheries is Schaefer (FAO, 2018).

Model convergence was assessed with Markov Chain Monte Carlo (MCMC) plots. In all scenarios, the MCMC plots indicated model convergence. In addition, the Reference Model appeared to fit CPUE data reasonably well, and run tests conducted on the log-residuals indicated that only the POR index possibly violated the hypothesis of

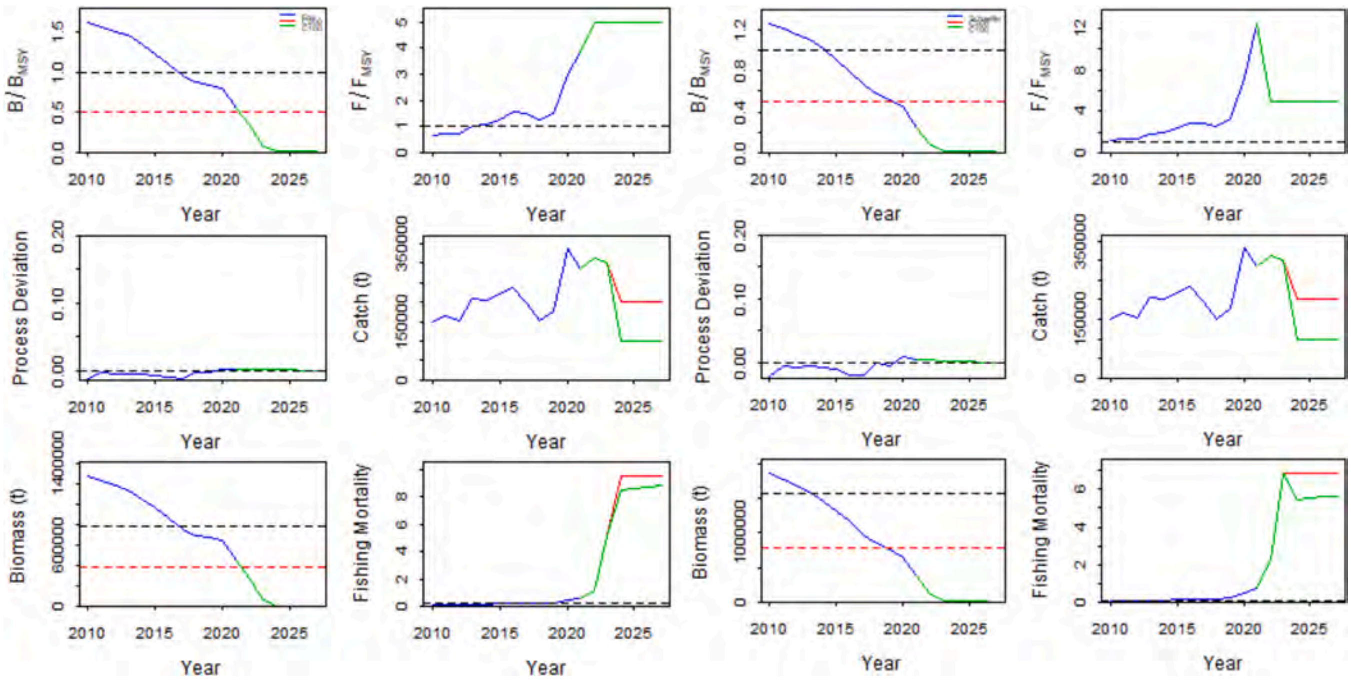

Fig. 16. Simulation of biomass and catch trajectory on the basis of setting a TAC according to the catch (average of 10 years) for flat sardinella.

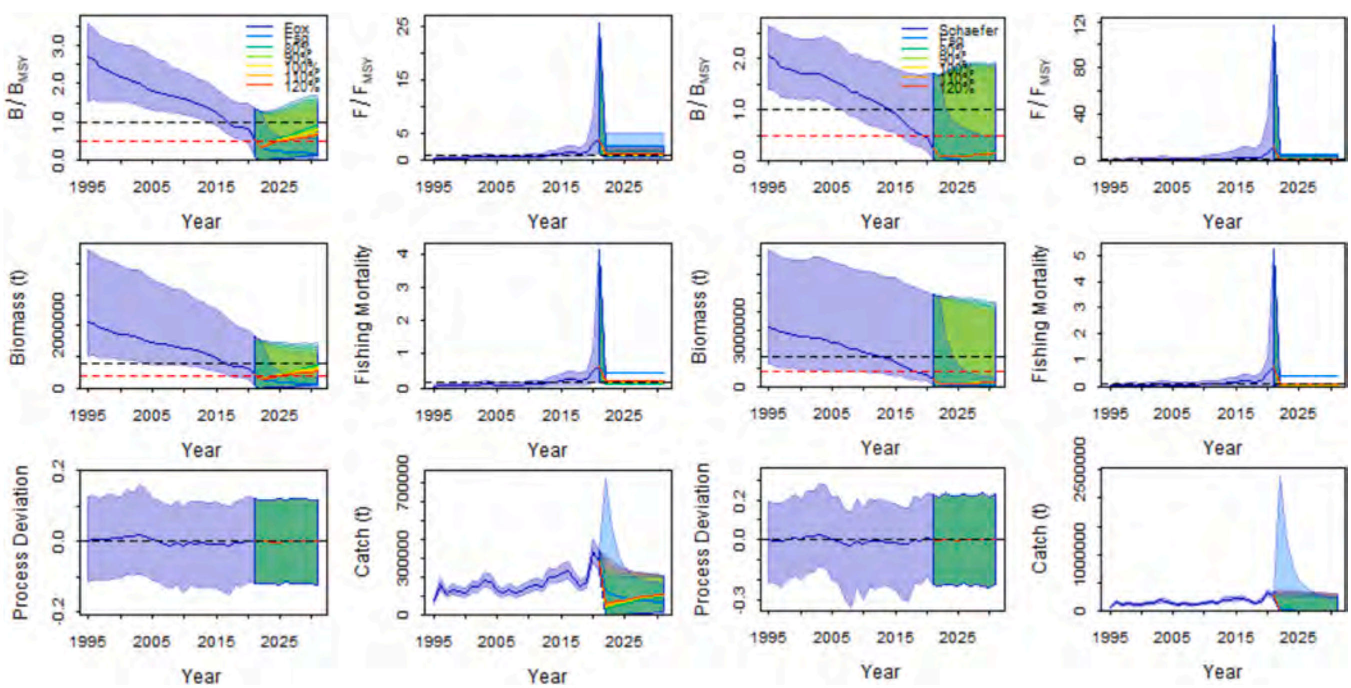

Fig. 17. Simulation of biomass and fishing mortality trajectories based on the Fmsy projection for flat sardinella.

randomly distributed residual patterns (see Supplementary Figure). Generally, the goodness-of-fit was adequate (RMSE is between 18.3 % and 19.2 % for the two models for round sardinella). For flat sardinella, the goodness-of-fit was adequate RMSE is no better (58.7–63.1 %), but within limits (see Supplementary Figure).

4.3. Round sardinella

The biomass trajectory has been drastically downwards and has worsened over the last six years, consistent with the fall in catch and abundance indices. Fishing mortality started to increase above sustainable levels from ∼2010, although it has declined in the last two years because of the collapse in catch. Overall these results paint an alarming picture of the status of this resource (Fig. 6). The current biomass compared to the MSY biomass of last year is very low, with a negligible probability of being above Bmsy. The different models converge during the last few years with a critical situation of this stock.

The results of an eight year retrospective analysis applied to the two model (Fig. 7) show a negligible retrospective pattern for the first 5 years (2016–2021) for round sardinella.

The surplus production phase plot for the Fox and Schaefer models corroborated the conclusion that the stock has been severely overexploited for several years (2013–2021). As a result, the Kobe biplot indicates that the stock has been in the red quadrant since 2013 (current probability 90 %) with the development of the purse seine fishery, and that the situation worsened after 2016 with the expansion of the purse seine fishery into the high productivity area of this stock (Fig. 8).

4.4. Flat sardinella

The results of the JABBA model, with the same scenarios, show high uncertainty around the biomass estimates, although with a convergence in the latter part of the time series. The trajectory as estimated by JABBA shows that the available biomass, which is lower than that of round sardinella, has fallen in recent years. Fishing mortality was fomerly low on this very coastal stock, with the fishing effort essentially directed towards round sardinella. However, fishing mortality on this species has increased in the last three years after pelagic fishing effort was redirected towards this species (Fig. 9).

The results of an eight year retrospective analysis applied to the two model (Fig. 10) show a negligible retrospective pattern for the first 5 years (2016–2021) for flat sardinella.

The surplus production phase plot for the Fox and Schaefer models indicates that the stock has been in the red quadrant since 2016 (current probability 95 %) with the development and expansion of the purse seine fishery in the high productivity area of this stock (Fig. 11).

4.5. Results of LBB model

The results of the size-based LBB model are in general more optimistic than those of the JABBA model.

4.6. - Round sardinella

The results of the LBB model also suggest that the round sardinella stock is overfished, or trending in that direction. The relative fishing mortality (F/M) is estimated at 1.5 in 2021. Biomass in 2021 is estimated at 40 % of initial biomass (B/B0 =0.40) (Fig. 12). Fishing mortality started to increase in 2017 with a strong increase in 2020 before falling slightly in 2021 where the availability of the species was low.

4.7. Flat sardinella

For the flat sardinella the result according to this method, the relative fishing mortality for flat sardinella (F/M) is 2.2 in 2021, also suggesting that the stock is overfished. The biomass in 2021 is estimated at 28 % of initial biomass (B/B0 =0.28) (Fig. 13). Fishing mortality started to increase in 2019 with a strong increase in 2020 and 2021 after the decline in round sardinella.

5. Discussion

For several years, the Fishery Committee for the Eastern Central Atlantic (CECAF) working group has been unable to assess the sardinella stocks due to lack of data. In the last three years, however, thanks to increased sampling carried out in Mauritania and Senegal, we have been able to apply two approaches for the assessment of the round sardinella stock.

The summary of the results of the different models applied to these two stocks can be summarized in the following table (Table 4):

The two species of sardinella fished in the northwest African region have been subject to increasing pressure in recent years. A rapid development of the fishery for these species in the coastal zone has been observed since 2017. Round sardinella has become rare in the last two years in the Senegal-Mauritania area. In the past, fishing effort was essentially oriented towards this species due to strong demand from African markets. For this reason, the exploitation rate of flat sardinella was moderate until 2018 when there was an almost total reorientation of the fishing effort towards this more coastal species. Since 2019, fishing pressure has increased further on flat sardinella and the biomass has declined. Emergency measures were taken in 2021, including the removal of the inshore purse seine fleet from the coastal zone.

Until 2012, the round sardinella in the Mauritanian area was fished by an industrial fleet authorized to fish beyond 13 miles from the coast, where mainly adults were encountered. The average size in the offshore fishery, although it has fallen, remains above 26 cm. The species was also exploited by an artisanal fleet using small purse seines. Since the number of units in this fleet was limited, the exploitation of the stock inside the 13 mile limit was very low until 2016. The results of the models show that since 2016, fishing mortality has increased simultaneously with the emergence of fishmeal factories (Corten et al., 2017) and overexploitation is now pronounced. This situation has been worsened since 2016 with the arrival of efficient semi-industrial Turkish purse seine vessels to supply the fishmeal factories in Mauritania. These vessels, whose number reached about 100 boats in 2018, fished for three years in the coastal spawning and breeding area of these two species (IMROP, 2019). For this reason, the CECAF Working Group started to raise the alarm that a collapse of the round sardinella stock was possible.

The modelling results suggest that as a result of the depletion of round sardinella, fishermen were prompted to direct their effort towards flat sardinella. An increase in mortality in this species has been observed (according to the JABBA model), bringing the stock into a situation of overexploitation for the last three years. This species, which is closely related to the round sardinella, performs more limited migrations, and the risk of a rapid collapse in areas of high fishing pressure is thereby more pronounced.

These results are consistent with, the CPUE values of *Sardinella* spp. for the offshore and artisanal fisheries in Mauritania from 2017 to 2021, which are the lowest values in the historical series, according to an analysis of the FAO regional working group, not yet published (CECAF 2022 WP).

The constant catch projections for round sardinella considering two scenarios (2021 catch and average catch for the last three years) suggest recovery of the biomass in 2023 and a decrease in mortality for the next three years (Fig. 14).

On the other hand, given that recent catches of round sardinella are low compared with historical catches, a population projection under a Fmsy scenario is shown in Fig. 15 for both the Fox and Scheafer models.

For flat sardinella, we conducted projections assuming the average annual catch for the last 10 years (~200000 t), as well as a more optimistic scenario with annual catch at half this level (100,000 t). The projections suggest a worrying situation for this stock, with a continual decline in biomass and an increase in fishing mortality (Fig. 16).

For projections based on Fmsy, the situation is also worrying for both models (Fig. 17).

The CECAF working group has long assumed that there is a large underexploited stock of flat sardinella in Mauritania's coastal waters. This assumption was based on the acoustic studies of the "Dr. Fridtjof Nansen", which normally showed a 50/50 ratio between round and flat sardinella in Mauritania (Fig. 5), whereas the catches of the commercial fleet were 80 % round sardinella. There is some speculation that data from the Nansen vessel overestimated flat sardinella due to low trawling speed, small net size and short haul duration. However, many people continued to believe that there was a large, under-exploited stock of flat sardinella in Mauritania, and this assumption was used to justify the development of the fishmeal industry. The present research shows that the assumption of a large, underexploited stock of flat sardinella in Mauritania was probably wrong, which explains the rapid decline of the fishmeal industry.

Regarding the selection of models, the two models give results which are quantitatively quite divergent from each other (see summary Table 4 above). The output of JABBA and LBB are qualitatively coherent (giving the same general conclusions about stock status) for flat sardinella; somewhat less so for round sardinella where the LBB is generally more optimistic about the state of the stock, suggesting a 60% depletion of biomass compared to the unfished level compared to the much more significant depletion estimated by the JABBA model. Overall, the authors consider that the results of the JABBA model are likely to be more robust: it uses more of the available data and the output is more coherent with direct biomass measurements from the acoustic surveys, as well as the perception of stock status from fishers in the region. It is not clear why the LBB results are divergent for round sardinella. It may be a consequence of data limitations; size-frequency sampling has been patchy in time and space because of limited resources, resulting in gaps in the sampling time series, particularly in from the southern part of the stock distribution. This increases the uncertainty in the analysis and potentially also results in bias. It may also result from inappropriate assumptions or priors, which could be explored further with additional sensitivity analyses. In any case, a precautionary management approach suggests that the results of the more pessimistic model should be incorporated into management advice in the short term, while focus continues on the development of the modelling and assessment framework by the CECAF Working Group.

In conclusion, this analysis provides more robust quantitative evidence for what has been suspected by the CECAF Working Group for several years, i.e. that both sardinella stocks are overexploited, while the round sardinella stock in particular could be critically depleted. Various factors are involved, but it is evident that a key one is the rapid growth of the fishmeal industry in the region, with the associated development of an efficient semi-industrial fleet operating in the coastal zone.

A realistic analysis is required across the region as to the level of catch and fishing effort that these stocks can support, firstly to allow rebuilding and secondly to operate the fishery on a long-term sustainable basis. These stock assessments provide an initial basis for this analysis.

Associated with this, there needs to be careful consideration by managers as a matter of urgency, on the actions required in the short term to avoid total collapse of the round sardinella, and allow rebuilding of both stocks to internationally-recognized management targets such as Bmsy.

In the longer term, managers must also consider how the estimated maximum level of sustainable catch and fishing mortality can be appropriately allocated between the different fleets in the different countries, to ensure that the future planning of the industry in countries across the region is consistent with the sustainability of these critical stocks. This is a very complex task, since it involves not only discussions between neighboring countries, but also difficult decisions within countries about the economic and socio-economic importance of different sectors of the fishery. It is critical that these reflections should start immediately.

CRediT authorship contribution statement

Cheikh Baye Braham: designed and planned the study. **Cheikh Baye Braham, Mohamed Ahmed Jeyid, Jilali Bensbai, Jo Gascoigne:** drafted the manuscript. **Cheikh Baye Braham, Mohamed Ahmed Jeyid, Jilali Bensbai, Jo Gascoigne:** analysed the data. **Cheikh Baye Braham** and **Jo Gascoigne** field work. All authors contributed to the article and approved the submitted version.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106873.

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