Comparing assessments of sardinella stocks in Senegal and Northwest Africa

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Abstract
This contribution compares stock assessments\textsuperscript{2} of sardinella species (\textit{Sardinella aurita} and \textit{S. maderensis}) off Senegal and neighboring countries performed from 2011 to 2013 using a now dated approach, i.e., surplus-production modelling (with and without considering environmental variability), with an assessment performed with the CMSY method. The results are similar and suggest that the fishery was near MSY in the 1990s, thus validating earlier suggestions that fishing effort should not have been allowed to increase beyond its 1990s level.

Introduction
This contribution compares stock assessments of sardinella species (\textit{Sardinella aurita} and \textit{S. maderensis}) performed by the first 3 authors a decade ago in the context of a consultancy for the Centre de Recherche Océanographique de Dakar-Thiaroye (CRODT) and the USAID-supported COMFISH Project, to the results that would have been obtained had the same data been analyzed with the recently-developed CMSY++ method (see oceanrep.geomar.de/id/eprint/52147/), which is improved over the CMSY method of Froese \textit{et al.} (2017).

In the following sections, a summary of the approaches and findings of the CRODT-COMFISH Project are presented, which jointly provide a context for the comparison with the CMSY++ method.

**Assessments by the CRODT/COMFISH Project (2011-2013)**

**Catch and biomass estimates**

A review of all catch and effort data available from the CRODT and Senegal’s DPM (Bureau of Statistics), the Food and Agriculture Organization (FAO) and fisheries projects and organizations covering the Region² encompassing The Gambia, Senegal, Mauritania and Morocco was carried out. Contradictions between data sets were resolved wherever possible.

In the process, a new abundance index for sardinella was developed, i.e., the mean CPUE at the Senegalese ports of Joal and Mbour, normalized for changes in fishing power of the standard fishing unit (two pirogues operating one *seine tournante*). The new abundance index uses artisanal data and includes the effects of technical change on the fishery from 1980-2011.

Well-fitted and robust Schaefer-type surplus-production models (Schaefer 1954, 1957; Ricker 1975; Pauly 1984) were constructed, and two variants, based on the CLIMPROD software (Fréon 1993), took explicit account of environmental changes.

The results of the project were strong enough to be used to inform decision makers and could have been safely included in Participatory Management Plans then (in 2013) being prepared to inform the CLPAs (Local Artisanal Fisheries Councils, to which management decisions are partially devolved under Senegal’s fishing laws) and other entities. Note that CLPAs cover areas much smaller than the sardinella stock(s), and thus must coordinate their action for positive results.

The Senegalese sardinella fishery was found to be overfished: an average artisanal Maximum Sustainable Yield (MSY) of 250,000 t·year⁻¹ could be taken with an effort of 115,000 pirogue (= canoe) trips per year instead of the then (2011) current 220,000 t·year⁻¹ at 155,000 trips·year⁻¹. CPUE was around 1.4 t·trip⁻¹ and would have increased to an average of 2.2 t·trip⁻¹ at MSY if effort were to be successfully reduced. Fishers operating pirogues would have received comparably higher incomes while the processing sectors (employing mainly women) would have handled around 20% more fish, making more available for local consumption.

The regional sardinella fishery (i.e., combining the sardinella fisheries of The Gambia, Senegal, Mauritania and Morocco) was also overfished: MSY of around 580,000 t·year⁻¹ occurred at effort which was then equivalent to 350,000 t·trip⁻¹ with a mean CPUE of 1.78 t·trip⁻¹. The actual average effort was then 28% higher at around 415,000 t·trip⁻¹ so the fishery produced only 500,000 t·year⁻¹ at CPUE of 1.2 t·trip⁻¹, around 48% lower than it could get (at MSY). These assessments, however, assumed that available official data on landings and effort are complete. However, a (then) recent report on Illegal, Unreported and Undocumented (IUU) fishing (Koutob et al. 2013) shows that:

(i) very large amounts of unrecorded fish – around 450,000 t·year⁻¹ have been taken since around 2005, in addition to the official landings reported in these assessments;

² In Northwest Africa, the 4 countries listed are considered to form a “Sub-Region.” Here, this will be referred to as a ‘Region,’ with the corresponding adjective being ‘regional.’
In spite of these issues, it may be possible to provide a reasonably accurate picture of the sardinella fishery in 2011, based on the following information:

- Official (artisanal) sardinella landings in Senegal were around 225,000 to 250,000 t·year$^{-1}$ taken at around 155,000 standard artisanal trips·year$^{-1}$;
- Another 200,000-250,000 t·year$^{-1}$ of invisible sardinella landings were taken by industrial IUU boats at an effort equivalent to or greater than 155,000 standard artisanal trips·year$^{-1}$;
- Real sardinella landings are probably around 500,000 t·year$^{-1}$, taken at an effort equivalent to or greater than 310,000 trips·year$^{-1}$, with a total biomass of less than 500,000 t;
- Thus, IUU catches will keep CPUE in the artisanal fishery low;
- In the absence of IUU fishing, the artisanal fleet would take much higher landings and CPUE than it does now.

Any attempt to increase artisanal CPUE without reducing or eliminating IUU fishing of sardinella would only increase artisanal effort at the cost of reducing artisanal CPUE and landings. Thus, sustainable fishing of Senegalese sardinella depends firstly on reducing or eliminating IUU fishing of sardinella: this is a necessary enabling condition, but is not a sufficient condition for achieving sustainability. The same reasoning is applied in this report to the regional sardinella stock: a second necessary, but not sufficient enabling condition for achieving sustainability is likely to be the reduction or removal of IUU fishing for sardinella in the entire Region.

A third necessary, but not sufficient enabling condition for sustainable sardinella fishing is the creation and implementation of a government unit for managing the sardinella fisheries that would coordinate the work of the CLPAs from Dakar Ouest to the Siné Saloum. A fourth necessary, but not sufficient condition for sustainable sardinella fishing in Senegal is a transparent and efficient regional strategy and a regional fishery management plan for sardinella, including strategies for locally appropriate management units in each country which will manage locally available resources.

Current work on how climate change impacts landings is not yet sufficiently advanced for results to be fully integrated into sardinella management. However, it is now clear that climate change does impact stocks. Managers now need to include this fact in assessments as a fifth necessary, but still not sufficient enabling condition needed to attain sustainable management.

Comprehensive bio-economic modeling carried out by CRODT/COMFISH Project (Dème et al. 2012) shows that Senegalese and regional sardinella fisheries were fished at or near the Open Access Equilibrium (i.e., generate zero net profits) in 2011. The strategy of aiming at MSY suggested above will increase profits, reduce costs and increase total and spawning biomass, and will probably be sufficient to ensure sustainable fishing (but will not secure MSY or a positive rent). More robust bio-economic modelling including for studies of fishing capacity management are needed to address the sixth and final necessary condition for achieving sustainable sardinella management in both Senegal and the regional context.

Dème et al. (2012) summarized all available estimates of sardinella biomass. These estimates are very useful for identifying the key sardinella spawning, nursery and grow out areas; notably, the review showed
a marked northward shift of sardinella grounds during the last few decades. This northward shift was related to higher sea temperatures in Senegalese waters and perhaps to a stronger upwelling, associated with intensifying coastal wind (Bakun 1990).

Modelling presented here shows that from 2008-2011 sea temperatures increased by around 2°C, and suggested that this may have increased (i) the Senegalese sardinella stocks (ii) regional landings. However, further temperature increases are likely to reduce regional and Senegalese landings of sardinella, e.g., over the next 1-2 decades because sardinella may migrate northwards to maintain itself in the water temperatures that they prefer (Cheung et al. 2009).

Addressing these six necessary conditions may be sufficient to achieve sustainable sardinella fishing. All enabling conditions must eventually be fulfilled for sustainable fishing to be achieved.

An informal review by the first author of biomass estimates from surveys in the Region carried out by European fisheries research vessels (e.g., the Norwegian R/V Fridtjof Nansen; Samb and Pauly 2000) suggests that several of their short-term surveys were conducted during periods or seasons of low stock biomass, thus giving misleading results. Available annual plots of biomass are therefore inaccurate representations of stock abundance and were ignored in this study. Regional vessels could provide spatially and temporally better resource coverage, leading to realistic biomass estimates which could be used to assess stocks more accurately than can be done currently.

By definition, fishing mortality (F) in a given year can be estimated from the catch (C) and the biomass (B) in that year (Sekharan 1974). Here combining echo-acoustic estimates of biomass (from the Norwegian R/V Fridtjof Nansen) and catches led to F values of 0.68 year\(^{-1}\) for \(S.\ aurita\) and 0.34 year\(^{-1}\) for \(S.\ maderensis\). Combining these with natural mortality (M) estimates of 0.66 year\(^{-1}\) and 0.65 year\(^{-1}\) (From Pauly 1980), respectively gives exploitation rates \(E = F/(M+F)\) of 0.51 for \(S.\ aurita\) and 0.34 for \(S.\ maderensis\). These results suggest that the stocks are heavily exploited, which is congruent with all the evidence available.

**Standardization of effort**
Because anecdotal evidence indicated that the fishing power of the sardinella fleet increased over time (see also Fitzpatrick 1996), we decided to carry out a first estimate of the changes in the fishing power of the standard sardinella fishing unit. CPUE and thus effort should be measured in a standardised way over time so that one unit of effort means the same for all boats and for different gear during the whole time series. We used CPUE data for the Senegalese ports of Joal and Mbour for this because:

- The fleets located in Joal and Mbour are relatively stable;
- These fleets generate around 80% of Senegal’s sardinella catch;
- None of the catch landed in these two ports originate from outside Senegalese waters;
- These fleets have access to many other species, e.g., Ethmalosa fimbriata and many other small pelagic fish species, and demersal fish and shrimp; thus, they do not need to follow sardinella schools as they migrate northwards.

Changing technology in Senegal could have biased estimates of CPUE, as it improved over the years and decades because of:

- increasing engine power which allows access to more distant and less heavily fished areas;
- increasing length and depth of nets;
• increasing numbers of fishers per fishing unit;
• use of larger boats/pirogues;
• use of echosounders and cell phones by fishers to improve the detection of fish schools;
• increasing fisher knowledge of fish and schooling behaviour, leading to new fishing strategies;
• other technical changes, many of which are peculiar to each fishery/gear/species.

These changes all tend to increase the fishing power of the standard fishing unit (i.e., the nominal effort), so that the effective effort has been underestimated in recent years. Such underestimates can lead to serious biases in assessments which risk misleading managers; notably, they can fail to detect reduced stock productivity, leading to optimistic management decisions which push the stock further towards reduced biomass, and eventual depletion.

Therefore, we used the cumulative effort and mean catch per unit of effort (CPUE) data from the artisanal fisheries, based in the ports of Joal and Mbour, to provide an assessment of the stock and of biomass trends for sardinella in Senegal and in the northwest Africa.

We used a qualitative method based on local knowledge to characterize the evolution of fishing power over time by interviews with fishermen and processors to reconstruct the history of fishing power in the artisanal seine fisheries in Senegal. The required questionnaire was developed and used in Joal, Mbour and St Louis in April 2013.

The standard fishing unit over the whole time series was:
• a large pirogue used for taking the fish;
• a smaller pirogue used for laying the net;
• a purse seine net (seine tournante);
• three outboard engines, one for each pirogue and one spare so that engine maintenance would not reduce fishing time.

Questions about the nature of a standard fishing unit were addressed to experienced fishers who had fished from the 1970s to 2011. Characteristics measured in this way included pirogue size (LOA), net size, number of crew, engine horsepower, number of engines, search time, and capacity for holding the sardinella catch. A summary of these interviews is presented Table 1, which allowed the estimation of an increase of power of 5.8% per year. Also, it appeared that the fishing power in the artisanal seine fisheries of the “Grande Côte” and the “Petite Côte” varied in the same way. Data shown in Table 1 were combined with data on number of trips to obtain the total standardised effort expended in each year. Figure 1 shows the observed and the adjusted effort obtained. The data in Table 1 were then combined with nominal effort (number of artisanal boats deployed in a given year (flatter, blue line in Figure 1) to obtain effective effort (ascending, red line in Figure 1).
Figure 1. Nominal vs. effective effort in the Senegalese artisanal fishery for sardinella, 1980 to 2011. Based on CRODT/DPM data, with corrections based on ‘a’ at the bottom of Table 1

Table 1. Summary of fishers’ responses regarding their perception of the past fishing power of pirogues (= canoes performing day trips) targeting sardinella and belonging to artisanal seine fisheries in St Louis and Mbour/Joal, in Senegal (May 2013)

<table>
<thead>
<tr>
<th>Item</th>
<th>'73 – '80</th>
<th>'80 – '90</th>
<th>'90 – '00</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOA (m)-setting unit (SM = small pirogue)</td>
<td>10</td>
<td>12</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>LOA (m)-carrying unit (large pirogue)</td>
<td>10</td>
<td>17</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Horsepower (hp)</td>
<td>25</td>
<td>40</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>kW (hp/1.34)</td>
<td>19</td>
<td>30</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Vessel Capacity Unit = (LOA·BR) + (0.45·kW)</td>
<td>168</td>
<td>390</td>
<td>725</td>
<td>806</td>
</tr>
<tr>
<td>Crew-setting unit</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Crew-carrying unit</td>
<td>10</td>
<td>12</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Net-length (m)</td>
<td>300</td>
<td>500</td>
<td>600</td>
<td>800</td>
</tr>
<tr>
<td>Net-depth (m)</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Capacity of pirogue (m)</td>
<td>230</td>
<td>551</td>
<td>1008</td>
<td>1350</td>
</tr>
<tr>
<td>CPUE (# of boxes = 45 kg per pirogue)</td>
<td>--</td>
<td>--</td>
<td>100</td>
<td>600</td>
</tr>
<tr>
<td>Power of pirogue (LOW·kW)/1000</td>
<td>373</td>
<td>866</td>
<td>1612</td>
<td>1791</td>
</tr>
<tr>
<td>Power of seine (L·D·Crew size)/1000</td>
<td>117,000</td>
<td>225,000</td>
<td>399,000</td>
<td>960,000</td>
</tr>
<tr>
<td>Total power per unit</td>
<td>117,373</td>
<td>225,866</td>
<td>400,612</td>
<td>961,791</td>
</tr>
</tbody>
</table>

a) The numbers in this row in the original (2013) version of this table were erroneous function, and generated an estimate of fishing power of 719% in 2011 (instead of the correct 819%), corresponding in an annual increase of fishing power of about 5.5% (instead of 5.8%). However, as even 5.5% is an extremely high estimate compared to the catchability increase data in Palomares and Pauly (2019), the original conversion from nominal to effective fishing effort is retained here, along with the various plots and parameter estimates based thereon.

Fitting surplus-yield models to the available catch and effort data

Catch of sardinella (in t wet weight) and effective effort data for three areas were analysed:

(i) The Joal/Mbour area where sardinella landings are less likely to contain landings taken outside Senegalese waters; these include around 80% of all sardinella landings made into Senegalese ports;

(ii) All catches landed into Senegalese ports; these include substantial catches taken in southern Mauritania and The Gambia since around 2000, so that the fishery assessed includes fish taken from the margins of neighbouring countries from around 2000 onwards;

(iii) All ‘regional’ sardinella catches, i.e., originating from The Gambia, Senegal, Mauritania and Morocco.
The catch (C) and effort (f) data for the 3 areas were first plotted as C/f (or CPUE) vs effort, and the intercept (a) and slope (b) of the resulting linear were regressions used to compute Schaefer-type parabola of (‘equilibrium’) catch or ‘yield’ vs effort from $Y = a \cdot f - b \cdot f^2$, with $MSY = a^2/2b - b \cdot (a/2b)^2$, and $f_{MSY} = a/2b$.

Figure 2 shows a pair of plots for each of the 3 geographical areas, with the plots on the left displaying the catch/effort vs effort from which the Schaefer-type plots on the right were derived. Note, however, that no adjustments were made to account for the fact that the catch data, given the rapid increase of effort, were not ‘equilibrium’ catches. The absence of such adjustment, e.g., through a method proposed by Gulland (1969), should have led to overestimation of MSY and the effort level that leads to MSY (Pauly 1984).

**Figure 2.** Surplus-yield modelling of the sardinella fisheries at 3 geographic scales in Northwest Africa. **A:** CPUE vs effort and **B:** surplus-yield model in Joal/Mbour area of Senegal; **C:** CPUE vs effort and **D:** surplus-yield model of sardinella landed in Senegal’s ports; **E:** CPUE vs effort and **F:** surplus-yield model in the Region covering The Gambia, Senegal, Mauritania and Morocco. Note that no adjustments were made to account for the fact that the catch data, given the rapid increase of effort, were not ‘equilibrium’ catches.
All three assessments show that the sardinella stocks around Joal/Mbour, the whole of Senegal and the entire Region are fished at effort levels beyond the level of effort required to take MSY. The results suggest that there is an excess of capacity in the Senegalese artisanal fishery so that effort/capacity reduction of around 35% will be needed to return to MSY in Senegal. The corresponding regional figure is 28%.

Figures 2D and 2F show that MSY and $E_{MSY}$ were reached from around 2003 for the Senegalese and regional fisheries respectively. However, Figure 2F also suggests that overfishing of the regional stock did not start until around 2008. Large-scale fishing by Senegalese boats in neighbouring EEZs is believed to have started around 2003 or a little later: such fishing may have been motivated by falling CPUE (Figure 2C) in the Senegalese artisanal fishery which fell from an average of around 3.4 t-trip$^{-1}$ in the early 1980s to around 2.2 t-trip$^{-1}$ around 2001, corresponding to a decline of 1.2 t-trip$^{-1}$. This fall will probably have reduced fisher incomes in a similar fashion.

**Surplus-yield modelling with environmental variables**

The potential impact of two environmental factors, increasing sea surface temperatures (SST) due to global warming and the intensification of the upwelling off Northwest Africa due to the intensification of coastal winds (Bakun 1990) were studied using the CLIMPROD software of Fréon (1993).

CLIMPROD can handle over 30 different surplus production curves based on underlying models including: (i) the standard Schaefer, Fox and Pella and Tomlinson models which assume that CPUE is influenced only by effort (ii) eight of models based on the assumption that CPUE is influenced by effort and that only catchability is influenced by an environmental variable (V) (iii) twelve models which assume that CPUE is influenced by effort and that only abundance is influenced by V (iv) four models for which it is assumed that CPUE is influenced by effort and that both abundance and catchability are influenced by V.

These models allow inclusion of biologically realistic assumptions about the number of exploited year classes ($N_{yr}$); the age at recruitment of the exploited species ($t_r$, years) and the incidence and ending of the effects of the environmental variable V. Based on the knowledge of sardinella life cycles in Senegal and the Region documented here, we assumed that:

(i) $N_{yr} = 3-4$ for the Joal/Mbour catches where the population is often dominated by juveniles;
(ii) $N_{yr} = 4$ years for the whole of Senegal and the whole region where adults are more abundant (we also found that assuming $N_{yr} \leq 2$ and $\geq 5$ led to inferior fits rejected them for these reasons);
(iii) $t_r = 1$ year for all cases;
(iv) V affects abundance and/or catchability from age 0 to age 1 for all cases.

Two environmental variables were used with the corresponding landings and effort data:

a. the CRODT Temperature Index (TI); and
b. the CRODT Upwelling Index (UI), both of which are specific to Senegalese waters.

Because UI and TI are specific to Senegal, they were used only to model the Joal/Mbour and the Senegalese fisheries.

Data were also available which reflected Atlantic Oscillation Index (AMO), but as this represents a large part of the Atlantic, it provided only a very poor fit for all data sets. This was probably because the AMO
has a long cycle of around 25 years while landings and effort data were only available from 1980-2011. During preliminary fitting, we found that all models which assumed that V affects catchability, or both catchability and abundance, either gave bad fits or provided no significant improvements over models which assumed that V affected abundance only, or that V had no effect. Therefore, we assumed that V could affect abundance, but did not affect catchability.

During preliminary fitting we also found that models for *S. maderensis* did not fit as well and/or were biologically less likely than those for *S. aurita*. Thus, given the smaller catches for *S. maderensis* and its biological similarity with *S. aurita*, we pooled the data for both species. It may be appropriate to revisit this decision when more comprehensive data are available.

The Schaefer-type models identified above, which describe the relations between catch and effort are robust enough to be used to identify management options. However, CLIMPROD may also be used to identify effects of environmental variables on C and CPUE, as well as effort. Various fits were made to data for the Joal/Mbour segment, and to the data for the whole of Senegal, using both the temperature index (V = TI) and the upwelling index (V = UI) available for Senegal (Figure 3).

With temperature, the best fit was obtained with the model CPUE = a(TI)+bf, where a and b are constants and CPUE and f are measured in t·trip$^{-1}$ and trips·year$^{-1}$ respectively.

Cury and Roy (1989) showed that intermediate levels of upwelling were associated with a high productivity of small pelagic fishes in upwelling systems, whereas weak and strong upwelling were associated with low productivity. This suggests a parabolic fit of the UI variable, and we found indeed that this formulation was optimal. Thus, the CLIMPROD presented here had the form CPUE = a + b·(UI) + c·(UI)$^2$ +d·f, where a is the intercept, and b, c and d are partial regression coefficient (slopes), and CPUE and f are measured in t·trip$^{-1}$ and trips·year$^{-1}$ respectively.

Figure 3 shows the temperature trend of off Senegal which, if it can be extended to the rest of the stock, especially Mauritania and The Gambia, may explain (at least in part), why both Senegalese landings (Figure 2D) and regional landings (Figure 2F) in the late 2000s and early 2010s years are higher than the
equilibrium curves suggest, as illustrated in Figure 4B (though this is also explained by the simple fact that effort increased).

**Figure 4:** CPUE vs effort (left) and surplus-yield models of the Senegalese sardinella fisheries accounting for environmental variables. A&B: Accounting for temperature, with the upper lines corresponding to 24.8 °C and the lower lines to 24.8 °C. C&D: Accounting for upwelling intensity (UI), with the upper lines corresponding to 1.9 UI units and the lower lines to 3.8 UI units (see also Figure 3).

This model in Figure 4B suggests that MSY is 50,000 t higher at 24.8 °C than at 22.8 °C (Table 2). A prudent fishing strategy could take 50,000 t·year⁻¹ less than suggested by the surplus-yield model for Senegal (Figure 2D), and 20,000 t·year⁻¹ less than the current ‘equilibrium’ landings. Although less fish would be landed, implementation of such a policy would increase the mean CPUE from around 1.6 t·trip⁻¹ to around 2.6 t·trip⁻¹.

**Table 2.** Temperature dependant estimates of MSY, fMSY and CPUE at MSY for the Senegalese sardinella fishery

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>MSY (t·yr⁻¹)</th>
<th>fMSY (trips·yr⁻¹)</th>
<th>t-trip⁻¹ at fMSY</th>
<th>2013 catch (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.8</td>
<td>200,000</td>
<td>100,000</td>
<td>2.00</td>
<td>150,000</td>
</tr>
<tr>
<td>24.8</td>
<td>250,000</td>
<td>110,000</td>
<td>2.27</td>
<td>230,000</td>
</tr>
</tbody>
</table>

The CLIMPROD model also suggests that stock productivity is low for values of UI < 1.9, intermediate at values near 2.8 and highest for values of UI ± 3.8 (Figure 4C and D).

**Overall results of the CRODT/COMFISH Project**

Assuming that all landings and effort data about the Senegalese and the Regional fishery are included in the data sets used here, the following conclusions can be made:

The new abundance index based on CPUE at Joal and Mbour, which accounts for the technological changes of the standard fishing units (seine tournante), can be combined with nominal effort data to produce robust and reliable Schaefer-type surplus-production models. These can be used to identify management options for decision makers.

Our analysis shows that the Senegalese fishery is overfished. The stock produced MSY of 250,000 t at 115,000 trips-year⁻¹ in 2003. In 2011, the fishery had landings of only 220,000 t at a much higher effort of 155,000 trips, i.e., 34% higher than the effort needed to take MSY.

CPUE fell in Senegal from around 3.4 t·trip⁻¹ in the early 1980s to around 2.2 t·trip⁻¹ in 2003, and to around 1.5 t·trip⁻¹ in 2011. Senegalese artisanal fishers’ complaints about “la rarefaction de la resource”
(i.e., the fish resource becoming rare) are entirely justified. If fishing effort in the fishery were to be reduced so as to produce MSY, CPUE would increase from current levels of 1.5 t·trip⁻¹ to around 2.2 t·trip⁻¹, i.e., by around 47%.

The regional model using the new measure of effective effort also shows that the sardinella fishery suffers from overfishing: MSY occurred at around 580,000 t and 325,000 effective artisanal trips per day, in around 2007 instead of the 2011 equilibrium yield of 500,000 t at around nominal 425,000 trips·year⁻¹. The fishery landed 80,000 t less and fished at 90,000 trips·year⁻¹ more than it would at MSY, so that it is heavily overfished with an excess capacity which is around 30% too high.

CPUE fell in the Region from around 3.25 t-trips⁻¹ in the early 1980s to around 1.08 t-trips⁻¹ in 2011, i.e., to around 33% of values in the 1980s, also confirming fishers' complaints about “rarefaction de la resource”. If the fishery is returned to MSY, the CPUE would rise to 1.78 t-trips⁻¹, i.e., it would increase by around 48%. (Note that most of the sardinella catch from outside but landed in Senegal are taken by industrial boats).

CPUE at MSY in the Senegalese fishery would be around 2.2 t-trips⁻¹ while regional CPUE in 2011 would be around 1.8 t-trips⁻¹. The Senegalese fishery is more productive, perhaps because Senegal’s EEZ has one of the most important nursery areas and juvenile grow-out areas for sardinella in the Region.

Mean water temperatures have increased during the study period and probably caused unusually high landings of Senegalese and regional landings since 2008. Higher temperature (a change in mean sea temperature from 22.8 °C to 24.8 °C) increased MSY from 200,000 to 250,000 t·year⁻¹ of sardinella.

Environmental surplus-production modelling showed that landings are influenced by both of the temperature and upwelling intensity. Models with good fits were obtained, but a more critical review of how these temperature and upwelling indices affect landings is needed before environmentally sensitive modelling can be fully integrated into fisheries management plans.

**CMSY sardinella assessments (2022)**

**Principle of CMSY**

The CMSY method of Froese *et al.* (2017), strongly improved from the Catch-MSY method of Martell, is, as the Maximum Sustainable Yield (MSY) concept, is based on an approach to fish population dynamics formulated by Schaefer (1954, 1957; see above). This approach, known as ‘surplus-production’ modelling, is based on the idea that a given ecosystem has, for any population, a distinct carrying capacity (k). If this population is diminished by external event (e.g., fishing), the population will grow back toward its carrying capacity. This growth depends on its intrinsic growth rate (r; here expressed in year⁻¹), which depends on the biological traits of the individuals of that population growth rate, size at first maturity, natural mortality, fecundity, etc.; see FishBase; [www.fishbase.org](http://www.fishbase.org), and by its current biomass (B).

Thus, fishing can maintain a population at any biomass level by withdrawing, each year, the biomass equivalent to the growth of that population. Because the production of new biomass is maximal when carrying capacity is halved (i.e., at k/2), MSY is produced when the unexploited biomass (B₀) is halved, and B₀ = k.
The CMSY method relies on this framework, and basically consist of tracing thousands of trajectories of the biomass of a stock and identifying the trajectories that are viable while compatible with the catches taken from this stock and some other constraints, or 'priors' (here 'viable' means not going extinct). The constraints are assumptions relating to the biomass reductions due to fishing, a range of possible estimates of carrying capacity (k) for the stock in the ecosystem in question, and a range of possible values of intrinsic rate of population growth (r).

Given a time series of catches, prior ranges of r and k values, thousands of biomass trajectories can be produced, of which very few can be viable. Moreover, the number of acceptable r-k data pairs is further reduced by reduced by the constraints relating to the biomass reductions due to fishing, expressed as fractions such as B<sub>end</sub>/k, B<sub>start</sub>/k or B<sub>int</sub>/k, relating to the 'biomass left' at the end of the available catch time series, at its start, or some intermediate value. Here, information from the first part of this contribution is used as priors (see Table 2).

Finally, the CMSY model can be turned into a Bayesian version of the full Schaefer model (BSM), by using CPUE data from other stock assessments, which usually results in reducing the uncertainty around estimates of MSY and related parameter estimates (see Froese et al. 2017).

The CMSY approach assumes that from one year (t) to the next (t+1), the biomass (B<sub>t</sub>) follows the equation:

\[ B_{t+1} = B_t + r(1 - B_t/k)B_t - C_t \]  

...1

where r is the intrinsic rate of population growth, k the carrying capacity (-B<sub>0</sub>), and C<sub>t</sub> the catch in year t. When the biomass (B<sub>t</sub>) declines below 0.25·k, Equation (1) is modified to allow reduced recruitment (= ‘depensation’):

\[ B_{t+1} = B_t + (4r B_t/k)(1 - B_t/k)B_t - C_t \mid B_t/k < 0.25 \]  

...2

where 4r·B<sub>t</sub>/k induces a linear reduction of population growth below B<sub>MSY</sub>/2, i.e., half of the biomass capable of generating maximum sustainable yield (MSY).

The R software that implements the CMSY method (or more precisely CMSY++, the version used here; see oceanrep.geomar.de/id/eprint/52147/) includes a routine that produces priors for k (Froese et al. 2017), whose output were accepted as defaults

\[ k_{low} = max(C)/r_{high} ; k_{high} = 4max(C)/r_{low} \]  

...3

where k<sub>low</sub> and k<sub>high</sub> are the default lower and upper limits of k, max(C) is the maximum catch in the time series, and r<sub>low</sub> and r<sub>high</sub> are the lower and upper limits of r-range, which is explored by the CMSY. Thus, we have:

\[ k_{low} = 2max(C)/r_{high} ; k_{high} = 12max(C)/r_{low} \]  

...4

with variables as in Equation (3).

Froese et al. (2017) formulated the BSM method such that the standard deviation of r in log-space is described by a uniform distribution (ranging between 0.001 irf and 0.02 irf), i.e.,

\[ irf = 3/(r_{high} - r_{low}) \]  

...5

where irf is an inverse range factor to infer the r-range, with r<sub>high</sub> and r<sub>low</sub> usually provided by FishBase (www.fishbase.org) for fishes (Table 1), and SeaLifeBase (www.sealifebase.org) for invertebrates.

The k estimation by BSM also assumes that k has a log-normal distribution, with the mean of k providing a credible estimate.
The BSM method allows the estimation of a catchability coefficient (q) that relates CPUE (when available) to biomass. Here, priors are given by:

\[ q_{\text{low}} = 0.25r_{\text{pgm}}CPUE_{\text{mean}}/C_{\text{mean}}; \quad q_{\text{high}} = 0.5r_{\text{high}}/CPUE_{\text{mean}} \]

where \( q_{\text{low}} \) and \( q_{\text{high}} \) define a (uniform) range of prior for the catchability coefficient; \( r_{\text{pgm}} \) is the geometric mean of the prior range for \( r \); \( CPUE_{\text{mean}} \) is the mean CPUE over the last few years, and \( C_{\text{mean}} \) is the mean catch over the same few years.

Finally, gradual improvements of the fishing boats, and of their gear, rigging, and instrumentation, which can be substantial, can be (and was) considered in BSM analyses, particularly when using industrial CPUE data, by including a technological ‘creep’ factor (Palomares and Pauly 2019). However, the recommended creep factor for periods around 30 years is about 3% per year.

The CMSY/BSM method has been applied to hundreds of ‘data-rich’ stocks, which enabled comparisons with the results of models requiring more data. It has also been applied successfully to multiple stocks in countries and regions with few ‘classical’ assessments, notably in Turkey (Demirel et al. 2020) and Northeast Asia (Liang et al. 2020; Zhai et al. 2020), with Palomares et al. (2020) representing a global application.

**CMSY application to sardinella catch data**

Samb and Pauly (2000) showed that the seasonal latitudinal migrations of sardinella from The Gambia and the South to Morocco in the North and back (see also Pauly 1994) preclude a real understanding of stock dynamics based exclusively on sub-national and even national data. Thus, CMSY++ (oceanrep.geomar.de/id/eprint/52147/10/CMSYUserGuideMarch2021.pdf) is here applied to the data in Table 3, pertaining to sardinella (mainly to \( S. \text{ aurita} \), combined with smaller catches of \( S. \text{ maderensis} \)) for the Northwest African Region, i.e., The Gambia, Senegal, Mauritania and Morocco.

The CMSY++ was run with a prior range for \( r \) of 0.5 to 1.2 year\(^{-1} \) from FishBase (www.fishbase.org) for \( S. \text{ aurita} \) and \( S. \text{ maderensis} \) and the following relative biomass priors: \( B_{\text{start}}/k = 0.3-0.7 \) and \( B_{\text{end}}/k = 0.1-0.5 \). Also, given the high estimate of 5.8% per year increase of gear efficiency, CMSY was run with a high estimate of technological ‘creep’ of 3% (Palomares et al. 2019).
**Table 3.** Catch and effort data. *Sardinella* spp. from Northwest Africa as used for the surplus-yield (Figure 2A&B) and CMSY++ assessments (Figure 5D-E)

<table>
<thead>
<tr>
<th>Year</th>
<th>Catch (t)</th>
<th>Effort</th>
<th>CPUE</th>
<th>Catch (t) used for assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>125,208</td>
<td>43,584</td>
<td>2.87</td>
<td>399,885</td>
</tr>
<tr>
<td>1991</td>
<td>142,069</td>
<td>44,953</td>
<td>3.16</td>
<td>320,320</td>
</tr>
<tr>
<td>1992</td>
<td>172,083</td>
<td>45,964</td>
<td>3.74</td>
<td>340,829</td>
</tr>
<tr>
<td>1993</td>
<td>160,386</td>
<td>47,026</td>
<td>3.41</td>
<td>267,900</td>
</tr>
<tr>
<td>1994</td>
<td>131,530</td>
<td>47,041</td>
<td>2.80</td>
<td>256,830</td>
</tr>
<tr>
<td>1995</td>
<td>128,788</td>
<td>47,962</td>
<td>2.68</td>
<td>287,930</td>
</tr>
<tr>
<td>1996</td>
<td>185,748</td>
<td>49,752</td>
<td>3.73</td>
<td>545,390</td>
</tr>
<tr>
<td>1997</td>
<td>156,853</td>
<td>51,031</td>
<td>3.07</td>
<td>525,760</td>
</tr>
<tr>
<td>1998</td>
<td>138,519</td>
<td>51,915</td>
<td>2.67</td>
<td>586,230</td>
</tr>
<tr>
<td>1999</td>
<td>107,644</td>
<td>52,800</td>
<td>2.04</td>
<td>487,020</td>
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<tr>
<td>2000</td>
<td>147,620</td>
<td>57,251</td>
<td>2.58</td>
<td>462,650</td>
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<tr>
<td>2001</td>
<td>179,054</td>
<td>61,921</td>
<td>2.89</td>
<td>461,650</td>
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<td>2002</td>
<td>140,712</td>
<td>70,412</td>
<td>2.00</td>
<td>460,650</td>
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<tr>
<td>2003</td>
<td>185,993</td>
<td>75,579</td>
<td>2.46</td>
<td>538,239</td>
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<tr>
<td>2004</td>
<td>161,375</td>
<td>76,694</td>
<td>2.10</td>
<td>512,450</td>
</tr>
<tr>
<td>2005</td>
<td>153,733</td>
<td>77,023</td>
<td>1.99</td>
<td>557,829</td>
</tr>
<tr>
<td>2006</td>
<td>110,738</td>
<td>83,643</td>
<td>1.32</td>
<td>467,320</td>
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<tr>
<td>2007</td>
<td>150,085</td>
<td>82,123</td>
<td>1.83</td>
<td>612,900</td>
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<tr>
<td>2008</td>
<td>152,158</td>
<td>85,690</td>
<td>1.77</td>
<td>617,110</td>
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<tr>
<td>2009</td>
<td>148,227</td>
<td>87,904</td>
<td>1.69</td>
<td>654,870</td>
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<tr>
<td>2010</td>
<td>143,446</td>
<td>92,318</td>
<td>1.55</td>
<td>679,800</td>
</tr>
<tr>
<td>2011</td>
<td>125,782</td>
<td>94,612</td>
<td>1.33</td>
<td>712,345</td>
</tr>
</tbody>
</table>

**Figure 5.** Output of the CMSY++ software running with catches of *Sardinella aurita* + *S. maderensis* from The Gambia, Senegal, Mauritania and Morocco for the years 1990 to 2011, and the priors mentioned in the text above. **A:** Catch (from Table X); **B:** viable combinations of r and k, with the blue cross referring to the most likely r-k pair compatible with the catches and prior information (see Table X), and the red cross to most likely r-k combination that also used the CPUE data in Table 3, thus leading to the BSM model in panel F; **C:** Narrower view of the viable runs. **D:** Stock biomass (blue line) and its (wide) 95% confidence interval, along with the CPUE series (dots), the corresponding trend line (red) and the green documenting the effect of the improvements, i.e., technological ‘creep’); **E:** Exploitation rate (F/F<sub>MSY</sub>) and its confidence interval, with the blue representing the median F/F<sub>MSY</sub> and the red line representing the trend of the CPUE (dots) converted into F/F<sub>MSY</sub> via F = f·q, where q is catchability. **F:** Equilibrium curve of the Schaefer-type model, showing that the high catches (blue line) and high CPUE (red line) of later years were not sustainable.
The results of the CMSY++ application to the data in Table 3 are shown in Figures 5 and 6. Figure 5A recalls the catch data used for this exercise (see Table 3, rightmost column), which were analyzed without (blue crosses in Figures 5B and 5C) and with the CPUE data from Joal/Mbour (see Table 3). Figures 5A, B, and C show the blue and red crosses to be close to each other, suggesting that the CPUE data and the regional catch data in Table 3 relate to similar biomass trends. Figure 5D, although slightly confusing, illustrates the same concept, i.e., that the biomass and the CPUE series have similar trends. Figure 5E illustrates the same notion, but in terms of $F/F_{MSY}$, while 5F, using a Bayesian surplus-production model, documents that the sardinella fisheries in Joal/Mbour and along the NW African coast were rarely in equilibrium, thus failing to meet fundamental assumptions of surplus-production modelling. Finally, Figure 6 shows the trajectory of the sardinella stock off NW Africa from high abundance and low fishing mortality (green panel) in the periods preceding the 1990s to the low abundance and overfishing status (red panel) in the 1990s, where they would remain despite various efforts to 'manage' the fishery.

**Figure 6.** Kobe plot illustrating the trajectory from under- to overfishing in the sardinella fisheries of N.W. Africa (see text).

**Discussion and Conclusions**

The exercise performed here comparing the results of an earlier approach with those obtained using a recently updated methodology leads to similar conclusions with both approaches: the sardinella stock(s) off NW Africa were at or near MSY in the 1990s, and the increase of effort that occurred in the 21st Century was excessive (see also Palomares et al. 2021).

This suggests that the modelling effort performed a decade ago led to management advice that was essentially correct, even if various assumptions of the surplus-yield models that were then used (notably the equilibrium assumption) were not met.

This, if anything, suggests that current debates about details of various stock assessment models may not matter when they are robust enough to point to the direction of the intervention(s) required to put a
fishery on a sustainable path. In the case of the Senegalese and NW African sardinella fisheries, the intervention that would have mattered is stopping the increase of, then reducing the effort expended by the fishery. However, this was not done.

The waste of resources that this implies is heightened by the recent development in NW Africa of using sardinella to produce animal feed for export (Pauly 2019). As a much-appreciated food for people, the Senegalese and others in the Region are deprived of nutritious, healthy food.

Acknowledgements
The surplus-yield assessments presented in the first part of this contribution are based on data and previous studies presented in spring 2013 to the CRODT and USAID COMFISH PENCOO GEJ in a consultant report funded by USAID as part of its support for developing marine fisheries management in Senegal. C.M. thanks his colleagues in Senegal who provided data and information that helped with the completion of this work. The second part of this contribution, was written in August 2022 by S.B. and D.P., who, together with CM, thank Elaine Chu for re-drafting all figures.

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