Assessment of 14 species of small pelagic fish caught along the coast of Northwest African countries[1]

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Abstract

The major stocks of small pelagic fishes in Northwest Africa move seasonally across the boundaries of the Exclusive Economic Zones of this sub-region's countries and, thus, must be assessed by pooling the catch and related data generated by national entities. Therefore, small pelagic catch data 'reconstructed' by the *Sea Around Us* from 8 Northwest African countries (Cape Verde, The Gambia, Guinea, Guinea Bissau, Liberia, Mauritania, Senegal, and Sierra Leone) was combined by 'marine ecoregions.' The assessment of 14 species was performed using the CMSY and BSM methods, complemented with 'priors' from the LBB methods and previous applications of the CMSY/BSM methods to national data. The CMSY and BSM methods, which are presented in some detail, generated time series of the biomass of these small pelagics, documenting serious depletions. There is an urgent need to rebuild the populations of small pelagic fish in the sub-region, particularly because their contribution to local food security is increasingly undermined by their use as raw material for fishmeal exports.

Introduction

Since the 1990s, evidence has been mounting that fisheries, almost everywhere, are in serious trouble due to huge increases in fishing effort and a declining global resource base (Tremblay-Boyer *et al.* 2011; Watson *et al.* 2013). Detailed stock assessments are available in many economically developed countries (e.g., the EU, Norway, the US, Canada, or Australia). They confirm large-scale resource depletion and provide a baseline for rebuilding efforts. Unfortunately, similar stock assessments are lacking for developing countries, in general, and Northwest Africa, in particular.

There are many reasons for this, notably: (a) lack of expertise, only slowly alleviated through various training workshops such as the one documented in this report, (b) the frequently cited "lack of data," and (c) the absence of methods to generate at least preliminary assessments with the limited data that are available. While (a) remains a real problem, (b) and (c) have been recently mitigated, through the development of computer-intensive methods relying mainly on fisheries catch time series.

A comprehensive global set of fisheries catch data now exists – the reconstructed catches of the *Sea Around Us*. These catches correct many of the worst problems associated with the database of landings (not catches!) disseminated by the Food and Agriculture Organization of the United Nations (FAO), which is largely based on unmodified submissions by its member countries (see Pauly and Zeller 2016a and www.seaaroundus.org).

The assessments presented here should provide an impression of the status of 14 stocks of small pelagic fishes caught in the Exclusive Economic Zones (EEZ) of 8 Northwest African countries (Cape Verde, The Gambia, Guinea, Guinea Bissau, Liberia, Mauritania, Senegal, and Sierra Leone). However, contrary to these reports and other contributions, we account for the stocks (except those caught in the EEZ of Cape Verde) 'straddling' the EEZ of 2 or more countries during seasonal migrations. Also, we use the

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'reconstructed' catch data of the *Sea Around Us* for these assessments, covering a longer time series (usually 1950 to 2016; see www.seaaroundus.org), i.e., longer than most national data sets.

Finally, we present the full set of equations derived for the Length-based Bayesian Biomass (LBB) method (Froese *et al.* 2018a, 2019) and by Froese *et al.* (2017) for the CMS/BMS method, to serve as reference, because none of the other contributions in this report included these equations.

Material and Methods

The LBB method

The Length-based Bayesian Biomass (LBB) estimation method (Froese *et al.* 2018) relies heavily on the von Bertalanffy growth function (VBGF; Bertalanffy 1938; Pauly 1998), used to depict the growth in body length.

$$L_t = L_{inf}\left[1-e^{-K(t-t_0)}\right] \quad ...1)$$

where L_t is the length at age t, L_{inf} is the mean length that the individuals of the species and stock in question would reach if they were to grow indefinitely (i.e., the 'asymptotic' length), K expresses the rate at which L_{inf} is approached (of dimension time^{-1}, usually year^{-1}), and t_0 is the age the fish would have at a length of zero if their growth always conformed to the VBGF even at younger ages (which it doesn't, but this does not matter for the LBB method, see below).

The majority of fish and invertebrate species grow throughout their lives and approach L_{inf} if there were no natural (M) or fishing (F) mortality. This is expressed by:

$$N_{t2} = N_{t1} \cdot exp\text{-}(Z\,(t_2\text{-}t_1) \quad ...2)$$

where N_{t1} and N_{t2} are the numbers of a given cohort or a population at time 1 and 2, and Z is the instantaneous rate of total mortality, consisting of natural and fishing mortality, i.e., $Z = M + F$ (Beverton and Holt 1957; Pauly 1998).

Fishing gears have distinct selection curves; the curve assumed in LBB is sigmoid, i.e., very small individuals ($<L_x$) are not caught, all individuals past a certain size ($>L_{start}$) are caught. In contrast, the faction caught between L_x and L_{start} is an increasing, *S*-shaped function of length. This can be expressed by

$$S_L = \frac{1}{1+e^{-\alpha\,(L-L_c)}} \quad ...3)$$

where S_L is the fraction of individuals retained by the gear at length L. In Equation (3), is the steepness of the S-shaped curve describing the gear's selectivity. Mean length at first capture (L_c) is the length at which half of the individuals encounter the gear will be retained by it.

Combining Equations (1) to (3) leads to:

$$N_{L_i} = N_{L_{i-1}} \left(\frac{L_{inf} - L_i}{L_{inf} - L_{i-1}}\right)^{\frac{M}{K} + \frac{F}{K} S_{L_i}} \quad ...4)$$

and

$$C_{L_i} = N_{L_i}\, S_{L_i} \quad ...5)$$

where N_{Li} is the number at length L_i, N_{Li-1} is the number at the previous length L_{i-1}, C is the number vulnerable to the gear, and all other parameters are as defined above. To reduce the parameter requirements, the ratios M/K and F/M are output - along with an estimate of L_{inf} - instead of the absolute values of F, M, and K. Note that F/M =(F/K)/(M/K).

LBB, while referring to 'L_c', considers Equation (3), i.e., accounts for the fish caught at small sizes (larger than L_x, but less than L_c) that are not compensated for by the larger fish not caught above L_c, but below L_{start} (Silvestre *et al.* 1991).

When more than one year's worth of L/F data is available, catch in numbers are made comparable between years through the division of both sides of Equation (5) by their sums:

$$\frac{C_{L_i}}{\sum C_{L_i}} = \frac{N_{L_i} S_{L_i}}{\sum N_{S_i} S_{L_i}} \quad ...6)$$

The ratios M/K and F/K can be computed by fitting Equation (4) to LF data (Figure 1).

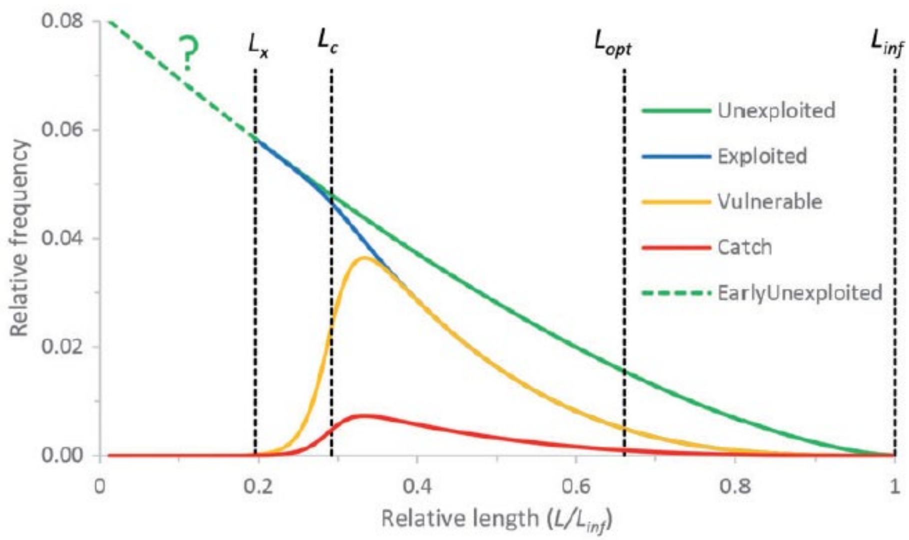

Figure 1. Illustrating the main features of the Length-based Bayesian Biomass (LBB) estimation method of Froese *et al.* (2018a). The red line is the part we can see, as derived from length-frequency samples. When fitted to L/F data (red), the LBB method allows inferences on the selection, growth and mortality processes which generated the underlying orange, blue, and green curves (see text).

Relative yield-per-recruit (Y'/R), as defined by Beverton and Holt (1966) can be computed, as presented by Froese *et al.* (2018a), from:

$$\frac{Y'}{R} = \frac{F/M}{1+F/M}\left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3(1-L_c/L_{inf})}{1+\frac{1}{M/K+F/K}}+\frac{3(1-L_c/L_{inf})^2}{1+\frac{2}{M/K+F/K}}-\frac{(1-L_c/L_{inf})^3}{1+\frac{3}{M/K+F/K}}\right) \quad ...7)$$

If CPUE is assumed proportional to biomass, dividing equation (7) by F/M leads to:

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

Thus, the relative biomass of a stock whose individuals are $>L_c$ is then given, if F = 0, by

$$\frac{B_0{>}L_C}{R} = \left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3(1-L_c/L_{inf})}{1+\frac{1}{M/K}}+\frac{3(1-L_c/L_{inf})^2}{1+\frac{2}{M/K}}-\frac{(1-L_c/L_{inf})^3}{1+\frac{3}{M/K}}\right) \quad ...9)$$

where B_o is the unfished biomass. Thus, the ratio of fished to unfished biomass is:

$$B/B_0 = \left(\frac{CPUE'}{R}\right)/\left(\frac{B_0'{>}L_C}{R}\right) \quad ...10)$$

(Froese *et al.* 2018a). Also, we have:

$$L_{opt} = L_{inf} \cdot 3/(3+M/K) \quad ...11)$$

where L_{opt} is the length when the biomass of a cohort of fish or invertebrates reaches its maximum (Holt 1958). This allows defining:

$$L_{c\_opt} = \frac{L_{inf}(2+3\frac{F}{M})}{\left(1+\frac{F}{M}\right)\left(3+\frac{M}{K}\right)} \quad ...12)$$

that defines the mean length at first capture, which maximizes both the catch and the underlying biomass for a given set of F/M and M/K ratios.

The LBB method has been applied successfully to numerous data-sparse stocks, notably in China (Liang *et al.* 2020a). It was applied in several contributions in this report and one of the stocks analyzed in this contribution.

The CMSY and BSM methods

The CMSY, as documented in Froese *et al.* (2016), is, like the Maximum Sustainable Yield (MSY) concept from which it gets its name, based on an approach to fish population dynamics formulated by Schaefer (1954, 1957; see Figure 2). This approach, also known as 'surplus-production' modeling, assumes that a given ecosystem has, for any animal population, a specific carrying capacity (k). If this population is reduced through an external event (e.g., fishing), the population will tend to grow back toward its carrying capacity. Such growth will depend on the intrinsic growth rate of a population (r; of dimension: time^{-1}), which is determined by the attributes of the individuals of the population in question (individual growth rate, age at first maturity, natural mortality, fecundity, etc.), and by the current abundance (B) of the population.

Thus, the abundance of a very small population cannot grow by a large amount, even if its r is relatively high because r·B is close to zero. Conversely, population growth is also low near carrying capacity because r·B is multiplied by 1-B/k, which expresses density-dependant effects. This results in high population growth occurring at intermediate abundance levels. The maximum occurs at k/2.

Thus, a fishery can maintain a given population at any given biomass level by removing, each year, an amount of biomass equivalent to the natural growth of that population. Because new biomass production is maximized at half-carrying capacity (k/2), MSY is obtained when the unfished biomass (B_0) is halved, assuming

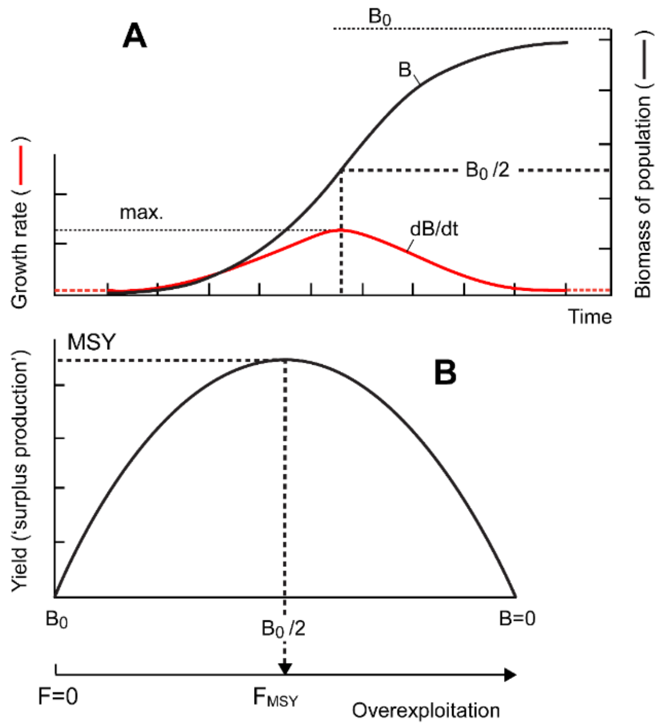

Figure 2. Basic principles behind (Schaefer-type) surplus-production models**. A**: the population size (i.e., biomass; B) of any living organisms (incl. small pelagic fish) will, if released into a new ecosystem, increase slowly, then rapidly, then again slowly as the carrying capacity of the ecosystem (B_0) is approached. **B:** The growth of that population (dB/dt), when plotted against biomass, generates a parabola, with low values of dB/dt (i.e., 'surplus production') both near carrying capacity and near B = 0. Surplus production has a maximum value at $B_0/2$, corresponding to Maximum Sustainable Yield. Surplus-yield predictions, and the CMSY method thus rest on a sound theoretical basis, since density-dependent limitation of carrying capacity is known to occur in all ecosystems (see text and Figure 3).

B_0~k. The CMSY method is built on this conceptual framework, essentially consisting of tracing random trajectories of its likely biomass for a given exploited stock and identifying the trajectories that remain viable while accommodating the catches taken from this population and a few other constraints (Figure 3). Here, 'remaining viable' means not going extinct. The constraints (or 'priors') are assumed biomass reductions caused by fishing, a range for the carrying capacity (k) of the species in the ecosystem in question, and a range of likely values of r, i.e., its maximum intrinsic rate of population growth. Qualitative measures of r, i.e., resilience (as defined in Musick 1999 and refined in Musick *et al.* 2000), are taken from FishBase (www.fishbase.org), which computes ranges of likely r values from biological parameters, especially the von Bertalanffy growth parameter L_{inf} and K, maximum age, and fecundity.

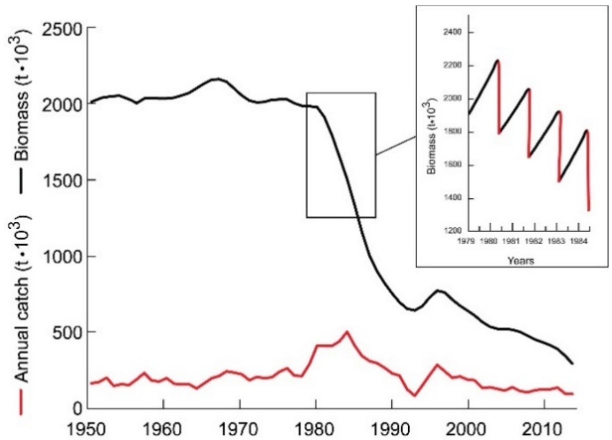

Figure 3. Illustrating the basic principle of the CMSY method: population biomass trajectories are projected from a start year (here 1950) where the biomass is assumed to be a (generally high) fraction of carrying capacity (k, or B_0) which increases via annual growth increments (as a function of population growth rate, r, and B/B_0) and decreases due to catches (in red, see insert). The trajectories that are retained are those that do not crash the population and conform to various constraints (see text).

In practice, given a catch time series and a wide range of r and k estimates, thousands of biomass trajectories can be generated, of which few are viable. Constraints refer specifically to independent prior knowledge of biomass levels. Thus, the reduction of biomass from carrying capacity by fishing at the start of the time series (e.g., 1950) is expressed as a fraction (B_{start}/k). Then, the likely fractions of biomass at some intermediate year (B_{int}/k) and at the end (B_{end}/k) of the catch time series are also obtained, e.g., from general knowledge about the fishery. Here, information from some of the national assessments in this report was used as priors (see Table 2).

Finally, the CMSY model was complemented by a Bayesian version of the full Schaefer model (BSM), which uses relative biomass time-series (e.g., catch per unit of effort or CPUE) from other stock assessments. This typically results in narrower estimates of fisheries reference points and good agreement with the age-based more-data-demanding assessments (see Froese *et al.* 2016, 2018b). This report presents the resulting B/B_{MSY} estimates of the CMSY analyses as an average of the last five years (2012-2016).

Another way of presenting the CMSY approach is to assume that from one year (t) to the next (t+1), the biomass (B_t) follows the equation:

$$B_{t+1} = B_t + r(1 - B_t/k)B_t - C_t \quad \text{...1)}$$

where r is the intrinsic rate of population growth, k is the carrying capacity (≈B_0), and C_t is the catch in year t.

When the biomass (B_t) falls below 0.25k, Equation (1) is modified to allow for 'depensation' (≈reduced recruitment):

$$B_{t+1} = B_t + (4\text{r}\, B_t/k)(1 - B_t/k)B_t - C_t \mid B_t/k < 0.25 \quad \text{...2)}$$

where $4rB_t/k$ creates a linear decline of population growth below B_{MSY}, i.e., half of the biomass capable of generating maximum sustainable yield (MSY).

The R software implementing the CMSY method includes a routine that produces wide (uniform) priors for k (Froese *et al.* 2017), whose output were accepted as defaults (as they were in the other contributions in this report):

$$k_{low} = \max(C)/r_{high}\,;\; k_{high} = 4\max(C)/r_{low} \quad ...3)$$

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

$$k_{low} = 2max(C)/r_{high}\,;\; k_{high} = 12max(C)/r_{low} \quad ...4)$$

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.,

$$irf = 3/\left(r_{high} - r_{low}\right) \quad ...5)$$

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

Table 1. Ranges suggested by FishBase (www.fishbase.org) for population growth rate (in year^{-1}) of the 11 West African species analysed in this study.

Resilience (r)	Suggested prior	Species
High	0.6-1.5	*Decapterus macarellus*, *Ethmalosa fimbriata*, *Ilisha africana*, *Sardinella aurita*, *Trachurus trecae*
Medium	0.2-0.8	*Caranx rhonchus*, *Engraulis encrasicolus*, *Mugil cephalus*, *Sardinella maderensis*, *Sardina pilchardus*, *Trachurus trachurus*
Low	0.05-0.5	–
Very low	0.015-0.1	–

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:

$$q_{low} = 0.25 r_{pgm} CPUE_{mean}/C_{mean};\, q_{high} = 0.5 r_{high}/CPUE_{mean} \quad ...6)$$

where q_{low} and q_{high} define a (uniform) range of prior for the catchability coefficient; r_{pgm} is the geometric mean of the prior range for r; $CPUE_{mean}$ is the mean CPUE over the last few years, and C_{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 of, e.g., 2 % per year (Palomares and Pauly 2019).

The CMSY/BSM method has been applied to hundreds of 'data-rich' stocks, which enabled comparisons with the results of models requiring more data (Froese *et al.* 2018b). It has also been applied successfully to multiple stocks in countries and regions with few 'classical assessments, notably Turkey (Demirel *et al.* 2019) and Northeast Asia (Liang *et al.* 2020b; Ju *et al.* 2020; Rena and Liu 2020), and globally (Palomares *et al.* 2020).

The catch and CPUE time series used for assessing small pelagics

The catch time-series data used for the present study are mainly based on FAO data, corrected and complemented through a procedure called 'catch reconstruction' documented in Zeller *et al.* (2007), Lam *et al.* (2016), Palomares *et al.* (2016), Zeller *et al.* (2016) and Pauly and Zeller (2016a). The actual reconstructions were largely performed on a per-country (or overseas territory) basis. Over 200 papers (*Fisheries Centre Working Papers*, chapters in *Fisheries Centre Research Reports*, book chapters and articles in peer-reviewed journals) document the time series reconstructions in 273 EEZs or parts thereof (see Pauly and Zeller 2016b).

The catch of industrial, artisanal, subsistence and recreational fisheries of each country was presented in these publications, based on landing and related data from FAO or the fisheries agency of the country in question, complemented with data (including discards) from each sector as required to obtain a complete time series, from 1950 to 2010 (now updated to 2016) of catches by the sectors mentioned above including estimates of illegal and previously unreported catches.

The difference between reconstructed *vs*. official catches can be considerable: for example, some countries that emphasize industrial tuna catches but neglect to document catches of nearshore reef fishes, which massively contribute to their food security (Zeller *et al.* 2015). Overall, the reconstructed catches for the 8 countries covered here amount to 256 million tonnes over the last 67 years, which is 4 % of the global total, and about 70 % higher than officially reported catches. Also, reconstructed catches are taxonomically disaggregated to a finer level than official catches. In some cases, this yielded a species-specific time series of dubious validity, depending on how the disaggregation was performed.

Tables 2 and 3 summarize the priors used in and results of the CMSY/BSM analyses of the stocks assessed in this report's various contributions, emphasizing on CPUE time series priors for relative biomass. Table 4 summarizes assessments published by FAO, which also informed our assessment of the 14 stocks belonging to 11 species of small pelagic fish presented in this contribution.

Marine ecoregions (MEs) vs EEZs

The EEZs that countries can claim since the United Nations Convention on the Law of the Sea (UNCLOS) was concluded in 1982 extend a maximum of 200 nautical miles from the coast of maritime countries and their territories. Over 90 % of the world's marine fisheries catch originates from EEZs. In some cases, e.g., around isolated islands, the inshore fauna belongs to a distinct ecosystem; hence their exploited fish populations can be treated as distinct 'stocks.' However, in most cases, the EEZs along countries' coasts encompass a range of different ecosystems. Therefore, to better address ecosystem issues in fisheries data and assessments, the more nuanced spatial system of marine ecoregions (MEs) is offered by the *Sea Around Us* in addition to EEZs and LMEs.

The Marine Ecoregions of the World (often referred to as MEOW, but here labelled MEs) are biogeographic entities along the world's shelves and coasts, as defined by Spalding *et al.* (2012). ME data and GIS shapefiles are available from a joint WWF/Nature Conservancy project. MEs have clearly defined boundaries and definitions and are generally smaller than LMEs (see Figure 4).

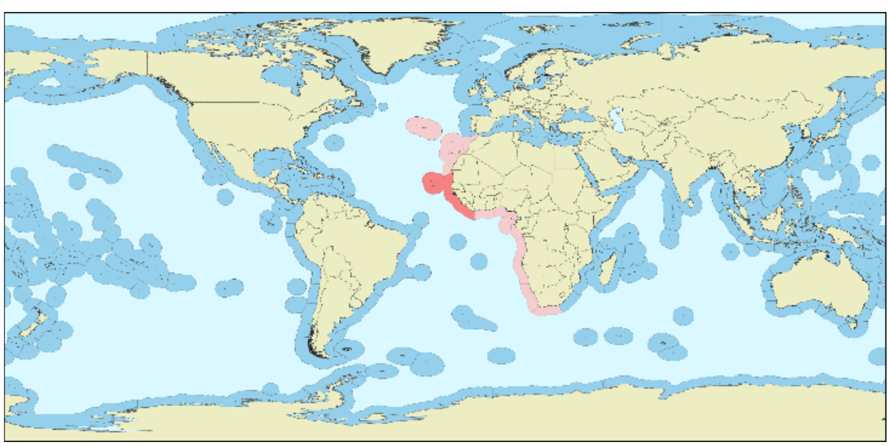

Figure 4. Map of the 232 Marine Ecoregions of the World (modified from Spalding *et al.* 2007). The 13 Marine Ecoregions overlapping with the Exclusive Economic Zones of West African countries are shown in pink. The MAVA Foundations operate operates in three of them (in red), i.e., the Cape Verde, Sahelian Upwelling, and Gulf of Guinea West.

Table 2. Priors used for the CMSY/BSM analyses by the authors of this report (**r** is in year^{-1}).

Countries	Species	Catch	CPUE	r	r range	k (10^3t)	B_{start}/k	B_{int}/k	B_{end}/k	Reference
Cape Verde	*Spicara melanurus*	1986-2015	-	-	1.4 - 4.4	Default	0.5-1.0	0.11-0.26	0.16-0.60	da Luz and Vieira (2020)
	Decapterus macarellus	1986-2015	-	1.08	0.71 - 1.62	Default	0.6-1.0	0.074-0.16	0.23-0.48	
The Gambia	*Ethmalosa fimbriata*	2005-2018	2005-2018	0.93	0.61 - 1.39	Default	Default	Default	Default	Sidibeh *et al.* (2020)
Guinea	*Ethmalosa fimbriata*	1995-2018	-	1.93	0.61 - 1.40	Default	Default	Default	Default	Soumah *et al.* (2020)
	Pseudotolithus elongatus	1995-2018	-	0.52	0.34 - 0.78	Default	Default	Default	Default	
Guinea-Bissau	*Galeoides decadactylus*	2000-2018	2000-2016	0.49	0.32 - 0.73	Default	0.2-0.6	0.01-0.5	0.01-0.3	Barri *et al.* (2020)
	Farfantepenaeus notialis	2000-2018	2000-2016	0.46	0.30 - 0.69	Default	Default	Default	Default	
Liberia	*P. senegalensis*	2009-2818	2009-2018	0.54	0.36 - 0.82	Default			0.01-0.4	Wehye & Palomares (2020)
Mauritania	*Engraulis encrasicolus*	2004-2018	-	0.59	0.39 - 0.91	158-1145	0.1-0.5	00.1-0.4	0.2-0.49	Jeyid *et al.* (2020)
	Sardinella aurita	1990-2018	1995-2012	0.74	0.46 - 1.16	Default	0.5-0.8	-	0.4-0.8	
	Ethmalosa fimbriata	2001-2018	2001-2017	0.93	0.61 - 1.39	Default	0.1-0.5	0.5-0.9	0.1-0.4	
	Octopus vulgaris	1991-2018	1991-2018	0.81	0.53 - 1.21	31-282	0.2-0.6	0.2-0.6	0.01-0.4	
Senegal	*Sardinella aurita*	1982-2017	1982-2017	0.74	0.46 - 1.16	Default	0.9-1	Default	Default	Thiaw (2020)
Sierra Leone	*Albula vulpes*	2008-2018	2008-2018	-	0.05 - 0.5	7.5–244	0.1-0.5	0.5-0.9	0.4-0.8	Showers and Turay (2020)

Table 3. Results of the CMSY/BSM analysis from the contributions in this report (k and MSY are in 10^3 tonnes). Only BSM results are shown for the stocks for which both BSM and CMSY were performed. CI=confidence interval.

Countries	Stock	Prior r (CI)	Prior k (CI)	MSY (10^3) (CI)	B_{end}/k	B_{end}/B_{MSY}	Exploitation (F_{end}/F_{MSY})	Reference
Cape Verde	*Spicara melanurus*	0.557 (0.395-0.785)	3.7 (2.37-5.77)	0.516 (0.406-0.654)	0.361	0.722	1.560	da Luz and Vieira (2020)
	Decapterus macarellus	1.2 (1.02-1.41)	7.120 (6.18-8.19)	2.13 (2,020-2.25)	0.401	0.802	0.609	
The Gambia	*Ethmalosa fimbriata*			15		0.892	1.32	Sidibeh et al. (2020)
Guinea	*Ethmalosa fimbriata*	1.13 (0.98-1.37)	199 (131-299)	55.7 (36.3-85.6)	0.37	0.739	1.76	Soumah et al. (2020)
	Pseudotolithus elongatus	0.73 (0.68-0.78)	44.5 (38-52)	8.1 (6.8-9.7)	0.29 (0.03-0.39)	0.593	1.52	
Guinea-Bisseau	*Galeoides decadactylus*	--	--	3189	--	--	--	Barri et al. (2020)
	Farfantepeneaus notialis	0.55 (0.449-0.674)	9.69 (6.93–13.55)		0.0872		0.705	
Liberia	*Pseudotolithus senegalensis*	0.667 (0.522-0.854)	4.46 (3.47-5.73)	0.744 (0.630-0.879)	0.337	0.674	2.38	Wehye & Palomares (2020)
Mauritania	*Engraulis encrasicolus*	0.73 (0.59-0.9)	689 (474-1001)	123 (105-144)	0.173	0.346	0.718	Jeyid et al. (2020)
	Sardinella aurita	0.76 (0.51-1.11)	2771 (2176-3529)	524 (399-689)	0.55 (0.37-0.78)	1.11	0.93	
	Ethmalosa fimbriata	0.93 (0.61-1.39)	277 (212-361)	69.4	0.35 (0.24-0.58)	0.70	0.982	
	Octopus vulgaris	0.95 (0.79-1.15)	123 (100-152)	294 (269-320)	0.39	0.78	1.37	
Senegal	*Sardinella aurita*	1.17 (0.872-1.57)	628 (500-790)	184 (165-205)	0.48	0.89		Thiaw *et al.* (2020)
Sierra Leone	*Albula vulpes*	0.13 (0.062-0.27)	26.3 (16.8-41.2)	0.810	0.48 (0.26-0.68	0.419	1.87	Showers and Turay (2020)

Table 4. Stock assessments of northwest African small pelagic stocks conducted by the Fishery Committee for the Eastern Central Atlantic working groups. Adapted from FAO (2019a, 2020a and 2020b); catches are in t per year, and their averages refer to the 2013-2018 period.

Species	Catch in 2018	Average catch	$B_{2018}/B_{0.1}$	$F_{2018}/F_{0.1}$	Assessment[2]	Reference
Caranx rhonchus South[1]	2,000	13,000[3]	–	–	–	FAO (2019a)
Caranx spp. South[1]	1,524[4]	2,116[4]	–	–	–	FAO (2019a)
Decapterus spp. South[1]	4,796[4]	6,070[4]	0.92[4]	0.95[4]	Fully exploited	FAO (2019a)
Engraulis encrasicolus	24,000	24,000[4]	–	0.69[5]	Fully exploited	FAO (2020a)
Ethmalosa fimbriata	48,000	70,000	–	1.56[5]	Overexploited	FAO (2020a)
Sardina pilchardus Zone A+B[1]	435,000	460,000	1.45	0.50	Not fully exploited	FAO (2020a)
Sardina pilchardus Zone C[1]	904,000	615,000	1.37	0.64	Not fully exploited	FAO (2020a)
Sardinella aurita	339,000	474,000	–	–	Overexploited	FAO (2020a)
Sardinella maderensis	80,000	190,000	–	–	Overexploited	FAO (2020a)
Sardinella spp. North[1]	419,000	665,000	–	–	Overexploited	FAO (2020a)
Sardinella spp. South[1]	60,047,000[4]	54,325,000[4]	1.29	0.49	Not fully exploited	FAO (2020b)
Scomber colias	419,000	379,000	1.23	0.84	Fully exploited	FAO (2020a)
Trachurus trachurus	99,000	118,000	0.83	1.19	Fully exploited	FAO (2020a)
Trachurus trecae North[1]	200,000	220,000	0.94	0.80	Fully exploited	FAO (2020a)
Trachurus trecae South[1]	31,487,000	22,032,000	0.75	1.25	Overexploited	FAO (2020b)

[1] The northwest African sardine stock is defined as three stocks, the northern stock (35°45'-32°N), the central (A+B) stock (32-26°N) and the southern stock (C) (26°N to the southern range of the species distribution; see FAO 2020). Note that here, we refer only with the central and southern stock overlapping with the region of the *Conseil Sous-Regional de la Pêche*. Note also that North refers to stocks in Mauritania, Senegal and The Gambia, while South refers to stocks in Guinea-Bissau, Guinea, Sierra Leone and Liberia.
[2] Equivalent CMSY B/k range: Not fully exploited > 0.6; fully exploited = 0.4-0.6; overexploited < 0.4.
[3] Average for 2014-2018.
[4] Refers to $Catch_{2017}$ (t), average catch for 2013-2017, $B_{2017}/B_{0.1}$ and $F_{2017}/F_{0.1}$.
[5] LCA-Y/R.

Adopting and presenting MEs as part of our spatial data system ensures that the stock assessments we performed for all maritime countries in the world, and to Northwest African countries in particular, are based on the well-established, data-poor CMSY/BMS methods (see above). The internal consistency in our global spatial data allocations is ensured in two steps: (1) we modified very slightly some ME boundaries to correspond to existing EEZ boundaries; and (2) we assigned the 232 MEs of Spalding *et al.* (2012) to our 273 EEZs (and parts thereof) as a function of the MEs' overlap with the EEZs

Results and Discussion

Based on the data in Tables 2, 3, and 4, we derived priors consistent with the biology of the 11 species studied here, and with the history of their exploitation, as presented below (see Table 5). Then, using these priors and the available ancillary data (see Table 5), we assessed 14 stocks of small pelagic fish; the results of these assessments are summarized in Table 6 and illustrated in Figures 6A and 6B. These results are detailed on a per-species bases in the following text, which concludes with a general overview of small pelagic fish's roles in Northwest Africa.

Caranx rhonchus

False scad (also known as *sareia-amarela* in Portuguese and as *diaî bou wekh* in Wolof), is a benthopelagic species found in marine and brackish water lagoons and estuaries, and which often forms schools near the bottom, usually at depths of 30-50 m (Bauchot 2003). False scad has been reported from a maximum depth of 200 m (Ly *et al.* 1996), and they range in the Eastern Atlantic from Morocco to Angola (Bauchot 2003), and possibly extending south to Namibia (Bianchi *et al.* 1999). The northern stock considered here straddles the Saharan Upwelling, Sahelian Upwelling, the Gulf of Guinea West, and Gulf of Guinea Upwelling marine ecoregions (see FAO 2002).

False scad is one of three major species of horse mackerels exploited by West African and European fleets, albeit as by-catch (FAO 2013, 2019b). The working group on assessing small-pelagic fishes off West Africa collects only catch data on this stock, i.e., there is no available CPUE data. The FishBase resilience category for this species (see Table 1) is based on 2 life-history parameters and the r-range from 1 stock assessment.[1] The B_{2016}/k range was assumed to be similar to that of horse mackerels (*Trachurus* spp.) in the region, i.e., 'overexploited' in Table 4 (equivalent range of 0.01-0.4; see Table 5).

False scad (*Caranx rhonchus*), occurring in Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone, was found to have a biomass corresponding to 0.59 of B/B_{MSY}, i.e., to be overfished (see Table 6).

[1] https://www.fishbase.ca/summary/Caranx-rhonchus.html.

Table 5. Priors used in the CMSY++ assessment of small-pelagic stocks in Northwest Africa.

Marine Ecoregion	Species	$Year_{start}$ catch	Relative biomass data	r-range	r_{BSM}	k_{BSM} (10^3t)	B_{start}/k	B_{int}/k	B_{end}/k
Northwest Africa[1]	*Caranx rhonchus*	1970	NA	0.21-0.48	NA	NA	NA	NA	0.01-0.40
Eastern Central Atlantic	*Decapterus macarellus*	1986	1986-2002[3]	0.71-1.62	0.872	23	0.2-0.6	NA	NA
West Africa[2]	*Engraulis encrasicolus*	1950	2000-2015[4]	0.39-0.91	0.618	1437	06.-1.0	0.2-0.6 2001	NA
Sahelian Upwelling	*Ethmalosa fimbriata*	1972	1995-2013[5]	0.61-1.39	1.01	257.6	0.4-0.8	NA	0.01-0.4
Gulf of Guinea West	*Ethmalosa fimbriata*	1950	1995-2016[6]	0.61-1.39	NA	NA	0.4-0.8	NA	0.01-0.4
Gulf of Guinea West	*Ilisha africana*	1992	NA	0.79-1.79	NA	NA	0.4-0.8[7]	NA	NA
Sahelian Upwelling	*Mugil cephalus*	1984	NA	0.34-0.77	NA	NA	NA	NA	02.-0.6[8]
Saharan Upwelling Sahelian Upwelling	*Sardinella aurita*	1976	1995-2009[9]	0.46-1.16	0.751	1134	0.2-0.6	0.1-0.5 1995	NA
Gulf of Guinea West	*Sardinella aurita*	1977	1995-2016[10]	0.46-1.16	0.675	196	0.1-0.5[11]	0.01-0.4 1995	NA
Saharan Upwelling Sahelian Upwelling	*Sardinella maderensis*	1967	1990-2014[6,9]	0.38-0.86	0.501	1023	0.6-1.0	NA	NA
Gulf of Guinea West	*Sardinella maderensis*	1970	1990-2012[10]	0.38-0.86	0.597	26	0.6-1.0	NA	NA
Saharan Upwelling Sahelian Upwelling	*Sardina pilchardus*	1966	1990-2016[9, 12, 13]	0.40-0.90	0.723	5126	0.6-1.0	NA	NA
Northwest Africa[1]	*Trachurus trachurus*	1990	1995-2015[9, 14]	0.31-0.72	0.606	649	0.4-0.8[15]	0.2-0.6 2000	NA
Northwest Africa[1]	*Trachurus trecae*	1990	1991-2015[9, 14]	0.73-1.65	0.764	1193	0.2-0.6	0.2-0.6[16] 2001	NA

[1] Mostly referring to marine ecoregions Saharan Upwelling, Sahelian Upwelling, Gulf of Guinea West, and may include Gulf of Guinea Upwelling.
[2] Includes marine ecoregions Saharan Upwelling, Sahelian Upwelling, Gulf of Guinea West, Gulf of Guinea Upwelling, Gulf of Guinea Central, Gulf of Guinea Islands, Gulf of Guinea South, Angolan, Namib, Namaqua and Agulhas Bank.
[3] CPUE based on the average of industrial and artisanal seine adapted from Table 1 of Stoberrup and Erzini (2006).
[4] Biomass estimates for Mauritania and Morocco by the R/V Dr Fridtjof Nansen and national vessels adapted from Table 6.3.2 of FAO (2019b).
[5] CPUE ($t \cdot trip^{-1}$) of encircling gillnets in Senegal adapted from Figure 7 of Ba *et al*. (2017).
[6] CPUE ($t \cdot trip^{-1}$) of industrial and artisanal fleets from Guinea-Bissau, Guinea, Sierra Leone and Liberia calculated from catch and fishing effort data presented in Tables 3.2.1 and 3.2.2 of FAO (2019a)
[7] LBB data from Stockholm and Isebor (1993) suggest B/B0=0.6 (see result of LBB analyses in Figure 5).
[8] There is no available assessment but exploited as by-catch in artisanal fisheries in Gulf of Guinea, and thus as a precautionary approach, setting B_{end}/k range as exploited.
[9] Biomass estimates for Mauritanian and Senegambian stocks by the R/V Dr Fridtjof Nansen adapted from Figure 7 of Lakhnigue *et al*. (2019).
[10] CPUE ($t \cdot trip^{-1}$) of pelagic trawl fleets from Guinea-Bissau and Guinea adapted from Table 2.3.1 of FAO (2019a).
[11] Mensah and Quaatey (2002) notes a near collapse of the Gulf of Guinea *S. aurita* stock in the 1970s.
[12] CPUE ($t \cdot trip^{-1}$) of Moroccan, European Gambian and Senegalese pelagic trawl fleets adapted from catch and effort data in Tables 2.2.1a and 2.2.1b of FAO (2016).
[13] CPUE ($t \cdot trip^{-1}$) of Moroccan purse seine fleets adapted from Figure 46 of INRH/DP (2017).
[14] Adapted from the Ram Legacy stock assessment database (RLSADB 2018).
[15] East European fishing fleets retracted from the region in 1990-1995 (see Bah and Sidibé, 2011 and Ould Taleb Sidi *et al*. 2011), which may be a reason for the low catches of horse mackerel at the start of the catch time series.
[16] $B_{2006}/B_{0.1}$ = 0.56 from Table 2 of Jalloh and Seisay (2011) used here as intermediate biomass range.

Table 6. List of small pelagic species considered in this study and which are found in the seven countries in which MAVA operates. All scientific names used here are currently valid and checked with FishBase. The catches (t; 1000^3) and B/B_{MSY} values are annual averages for the EEZ listed and the period 2012-2016.

Scientific name	English name	EEZ occurrence	Catch	B/B_{MSY}	Stock status
Caranx rhonchus	False scad	Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone	14.0	0.59	Overfished
Decapterus macarellus	Mackerel scad	Mauritania, Cape Verde Senegal, Gambia, G.-B, Guinea, Sierra Leone	2.92	0.41	Grossly overfished
Engraulis encrasicolus	European anchovy	Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone	139	0.46	Grossly overfished
Ethmalosa fimbriata	Bonga shad	Mauritania, Senegal, and Gambia	85	0.91	Slightly overfished
Ethmalosa fimbriata	Bonga shad	Guinea-Bissau, Guinea, and Sierra Leone	157	0.90	Slightly overfished
Ilisha africana	West African ilisha	Guinea-Bissau, Guinea, and Sierra Leone	9.21	1.5	Healthy
Mugil cephalus	Flathead grey mullet	Mauritania, Senegal, and Gambia	12.1	1.3	Healthy
Sardinella aurita	Round sardinella	Mauritania, Senegal, and Gambia	312	0.74	Overfished
Sardinella aurita	Round sardinella	Guinea-Bissau, Guinea, and Sierra Leone	87.2	0.38	Grossly overfished
Sardinella maderensis	Madeiran sardinella	Mauritania, Senegal, and Gambia	199	0.74	Overfished
Sardinella maderensis	Madeiran sardinella	Guinea-Bissau, Guinea, and Sierra Leone	53.3	0.79	Overfished
Sardina pilchardus	European pilchard	Mauritania, Senegal, and Gambia	1025	0.88	Slightly overfished
Trachurus trachurus	Atlantic horse mackerel	Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone	105	0.92	Slightly overfished
Trachurus trecae	Cunene horse mackerel	Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone	124	1.1	Healthy

Decapterus macarellus

Mackerel scad (also known as *cavala preta* in Kriolu) is a pelagic-oceanic species common at depths of 40-200 m (Smith-Vaniz 1986a) in most of the world's oceans. In the Eastern Atlantic, it occurs in St. Helena, Ascension, Cape Verde, and the Gulf of Guinea (Smith-Vaniz *et al*. 1990). Thus, it is considered a single straddling stock covering Mauritania, Cape Verde, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone (see Table 5).

Catch data from the *Sea Around Us* is almost entirely from Cape Verde, reflecting the importance of the mackerel scad in Cape Verdean fisheries. It made up 40% of the marine fisheries catch at its peak in the late 1990s, decreasing to about 20% in the mid-2000s (Stobberup and Erzini 2006). The FishBase resilience category of mackerel scad (see Table 1) is based on one estimate of the K parameter of von Bertalanffy Growth Function (VBGF) and an r-range based on 3 stock assessments.[1] These priors for r were used, along with CPUE data for 1986 to 2004 from the trawl fleets adapted from Stobberup and Erzini (2006), with a 2% annual technology creep applied to the CPUE data (Palomares and Pauly 2020). The CMSY++ analysis was set to a start year of 1986 to use the first year of the CPUE time series as a starting biomass window to peg the analysis to that year's CPUE level, which is equivalent to the FAO category 'exploited,' i.e., B_{1986}/k range of 0.2-0.6 (see Table 5).

Our assessment of the stock of mackerel scad (*Decapterus macarellus*) occurring in Mauritania, Cape Verde Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone estimated its relative biomass to be 0.41 of B/B_{MSY}, i.e., to be grossly overfished (see Table 6).

[1] https://www.fishbase.ca/summary/Decapterus-macarellus.html

Engraulis encrasicolus

The European anchovy (also known as *youssou nokoum* in Wolof) is a pelagic-neritic species, i.e., it is found mostly in coastal waters (see Riede 2004 and Frimodt 1995), occurring from the surface to depths of 400 m (Schneider 1990). It is widespread in the Eastern Atlantic from Norway (Bergen) to South Africa (Durban) and also in the Mediterranean, Black, and Azov Seas (Whitehead 1990 and Whitehead *et al.* 1988). European anchovy performs extensive seasonal migrations along the northwest African coast, which corroborates the assumption that this species has only one stock in the region (FAO 2016).

As the bulk of the catches in this region are reported by Mauritania (and Morocco; see Jeyid *et al.* 2020), using the biomass estimates from acoustic sampling by the *R/V Fridtjof Nansen* in 2000-2015 from Mauritania and Morocco (FAO 2019b; see also Table 5) is justified. This species has a medium resilience (see Table 1), as estimated from 3 life-history parameters in FishBase and an r-range based on 21 stock assessments[1] (see Table 5). The stock was assessed as 'overexploited' in 2014 (FAO 2016; $B_{2014}/k<0.4$) and as fully exploited in 2018 (FAO 2019b; $B_{2018}/k = 0.4\text{-}0.6$, see Table 4). As the stock can be considered to have a high carrying capacity ($k_{BSM} = 1437 \cdot 10^3$ t; see Table 5), we assumed that it was healthy at the beginning of the time series ($B_{1950}/k = 0.6\text{-}1.0$). Finally, since the stock devolved to an overexploited state in the 2000s (as suggested by the CPUE trend), we assumed a B_{2001}/k range of 0.4-0.6.

The stock of European anchovy (*Engraulis encrasicolus*) occurring along the coasts of Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone was assessed to have a relative biomass (B/B_{MSY}) of 0.46, i.e., to be grossly overfished (see Table 6).

Ethmalosa fimbriata

The bonga shad (also known as *galucha* in Portuguese and *kobo* in Wolof) is a shallow (0-50 m depths) pelagic-neritic (brackishwater) species belonging to the Clupeidae Family that migrates from freshwaters (as far as 300 km up river; see Teugels 2007) to the coast to spawn (Riede 2004). It is found in the Eastern Central Atlantic, from Western Sahara (Dakhla) to Angola (Lobito Bay; see Gourène and Teugels 2003). Genetic studies divide the bonga shad into two stocks recognized in the region as the northern (Mauritania, Gambia, Senegal) and southern (Guinea, Guinea-Bissau, Sierra Leone, Liberia) stocks (Durand *et al.* 2012).

Important artisanal fisheries in northwest Africa exploit the northern stock of bonga shad (see Sidibeh *et al.* 2020). Using purse seines and encircling gillnets, their profits have declined due to the increasing costs of larger fleets exploiting a decreasing bonga shad biomass (Ba *et al.* 2017, Figure 7). Fishing effort and catch time series from this fishery were used in the CMSY++ analysis (1995-2013; see Table 5). Catch data heuristics suggested 1972 as the start year when the stock was not overexploited ($B_{1972}/k = 0.6\text{-}1.0$). Given an $F_{2017}/F_{0.1} = 1.45$ estimated by FAO (2020a, b), we assumed an overexploited status ($B_{2016}/k<0.4$) in the final year of the time series.

The southern stock was assessed as locally intensively exploited in the mid-1970s (see Everett 1976), which provides a biomass window for the start of the time series (B_{1950}/k set at 0.4-0.8; see Table 5). The CMSY++ analysis was run with CPUE time series (1995-2016) from industrial and artisanal fleets of Guinea-Bissau, Guinea, Sierra Leone, and Liberia calculated from catch and fishing effort data presented in Tables 3.2.1 and 3.2.2 of FAO (2019a). The final year biomass window was based on the FAO (2020a) assessment of this stock being overexploited in 2018 in the whole sub-region ($B_{2016}/k<0.4$). The FishBase resilience category (see Table 1) used for both stocks was based on 3 life-history parameters and the r-range based on 5 stock assessments.[2]

The northern stock of Bonga shad (*Ethmalosa fimbriata*), occurring in Mauritania, Senegal, and The Gambia was found to be slightly overfished, with $B/B_{MSY} = 0.91$, like its southern stock, occurring off Guinea-Bissau, Guinea, and Sierra Leone, for which $B/B_{MSY} = 0.90$.

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[1] https://www.fishbase.ca/summary/Engraulis-encrasicolus.html.

[2] https://www.fishbase.ca/summary/Ethmalosa-fimbriata.html

Ilisha africana

The West African ilisha (also known as *capasseca* in Portuguese and *lati* in Susu and Krio) is a pelagic-neritic species found from the surface of the water column to depths of 35 m (Poll 1953). It inhabits coastal areas along beaches, brackish water lagoons and estuaries and may penetrate freshwaters (Fischer *et al.* 1981). This study assumes one stock for the Gulf of Guinea West marine ecoregion.

The West African ilisha is an important bycatch of the sardinella and shrimp trawl and purse seine fisheries in Ghana, Benin and Nigeria, i.e., the southern part of the Gulf of Guinea West marine ecoregion (Whitehead *et al.* 1988; Ajayi and Adetayo 1982). No official assessments are available; however, estimates of Z/K = 3.7 and F/Z = 0.44 from distinct coastal populations caught along with sardinella in Benin suggest an 'underexploited' stock (Edmond *et al.* 2017).

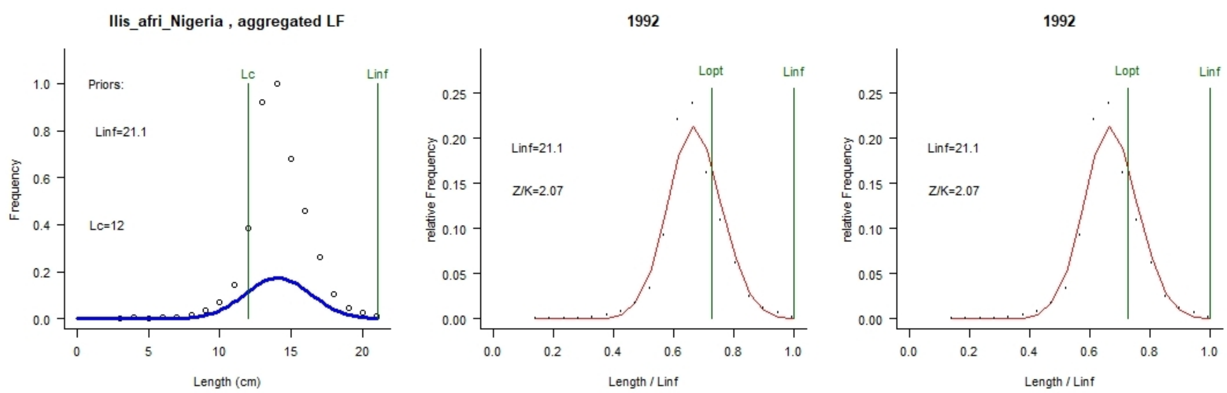

Figure 5. Result of the application of the LBB method to length-frequency data sampled from artisanal fleets in Benin and Nigeria primarily targeting *Ilisha africana* (Stockholm and Isebor 1993) suggesting a $B_{1992}/B_0 = 0.6$ used as prior in the CMSY analyses presented in this study (see Table 5).

The CMSY++ analysis was run from 1992 as suggested by catch data heuristics. A B_{1992}/k range of 0.4-0.8 (see Table 5) was used based on the results of the LBB model run on length-frequency data from Benin and Nigeria (Stokholm and Isebor 1993) suggesting a $B_{1992}/B_0 = 0.56$ (see Figure 5). The FishBase resilience category (see Table 1) of this species was based on a range of K values while the r-range was based on 3 stock assessments.[1]

Our CMSY assessment of West African ilisha (*Ilisha africana*), occurring of Guinea-Bissau, Guinea, and Sierra Leone, is that the stock currently exceeds the biomass required to generate MSY, i.e., $B/B_{MSY} = 1.5$ (Table 6), which is also corroborated by the LBB analysis in Figure 5.

Mugil cephalus

The flathead grey mullet (also known as *mulet grosse tête* in French) is found in all tropical, subtropical, and temperate coastal waters (common at depths of 0-10 m but reaches depths to 120 m; see Harrison 1995) often in brackish water lagoons and estuaries, and can reach up-river (Riede 2004). In the Eastern Atlantic, it spans from the Bay of Biscay to South Africa, including the Mediterranean and Black Seas (Thomson 1990). The stock considered in this study is that of the Sahelian Upwelling marine ecoregion as it is an important resource, e.g., in Senegal.

This stock is exploited as bycatch by the artisanal fisheries in the Gulf of Guinea (see Nunoo and Asiedu 2013). CPUE, biomass or length-frequency data could not be identified for this stock. The CMSY++ analysis was run with start year in 1982 based on catch data heuristics. The resilience category for this species from FishBase (see Table 1) was based on four life-history parameters and the r-range was based on 12 stock

[1] https://www.fishbase.ca/summary/Ilisha-africana.html

assessments (see Table 5).[1] A precautionary approach B_{2016}/k range of 0.2-0.6 was used, i.e., fully exploited, assuming continued exploitation of this stock since 1950.

Our results suggest that the stock of flathead grey mullet (*Mugil cephalus*) off Mauritania, Senegal, and The Gambia is healthy, with B/B_{MSY} = 1.3 (see Table 6).

Sardinella aurita

The round sardinella is also known as *tayit* (Arabic, Hassaniya), *sardinelle ronde* (French), *sardinella* or *sardinha* (Portuguese), *bonga séri* (Susu), and *yaboï maureug* (Wolof), to list a few of the many names used for this commercially critical pelagic species. It is oceanodromous (Riede 2004) in the Atlantic Ocean. In West Africa, it occurs from Gibraltar to South Africa (Saldanha Bay), notably in upwelling areas from Mauritania to Guinea (see Teugels 2007 and Cury and Fontana 1988). The round sardinella prefers clear saline coastal waters from the surface to depths of 350 m, preferring cold waters at 18-24°C (see Bianchi *et al*. 1999; Whitehead et *al*. 1988). Juveniles are found in shallow brackishwater nursery areas and migrate as adults to colder offshore waters (Whitehead 1985). Two stocks are recognized in our study area, the northern (Saharan and Sahelian Upwelling marine ecoregions) and southern (Gulf of Guinea West) stocks (FAO 2019a).

Biomass data used to inform the CMSY++ analysis for the northern stock were from the R/V Fridtjof Nansen acoustic surveys from Morocco, Mauritania and Senegal in 1995-2015 adapted from Lakhnigue *et al*. (2019, Figure 7). Heuristics of the catch data suggested a start year in 1976, and B_{1976}/k range of 0.2-0.6 (fully exploited) based on the importance of this stock in the region since the fishery began in 1967 (Lakhnigue *et al*. 2019). The intermediate biomass window used in the analysis was based on the 1995 biomass data from Lakhnigue *et al*. (2019), indicating a B_{1995}/k ~ 0.3 (see Table 5).

The southern stock was analyzed with CPUE data from Guinea and Guinea-Bissau's pelagic trawl fleets (FAO 2019a, Tables 2.3.1a). Catch data heuristics suggest a start year at 1977. Based on the southern stock's near collapse in the Gulf of Guinea in the early 1970s (Mensah and Quaatey 2002), a B_{1977}/k range of 0.1-0.5 was used. The intermediate biomass window was set at 1995 based on the CPUE data with a B_{1995}/k range of 0.01-0.4 based on an FAO (2019b) assessment of the stock's poor health (see Table 5).

The FishBase resilience category (see Table 1) for the species was obtained from three life-history traits, and the r-range was based on 12 stock assessments.[2]

The assessment of the round sardinella (*Sardinella aurita*) off Guinea-Bissau, Guinea, and Sierra Leone suggest that it is grossly overfished, B/B_{MSY} = 0.38 (see Table 6).

Sardinella maderensis

The Madeiran sardinella is also known as *grande allache* in French, *arenque* in Portuguese, or *yaboî tass* in Wolof. Despite what its name may suggest, it is found throughout the West African coast from Gibraltar to Angola (Gourène and Teugels 2003) and in the southern and eastern parts of the Mediterranean Sea and into the Suez Canal (Whitehead 1985). This species forms schools, preferring waters at 24°C and migrates from Gabon to Angola and from Sierra Leone to Mauritania, usually in association with upwelling seasons, with juveniles staying in shallow water nurseries in brackishwater lagoons and estuaries (Riede 2004). Two stocks are considered here, the northern (Saharan and Sahelian Upwelling marine ecoregions) and southern (Gulf of Guinea West) (FAO 2019a).

Several CPUE data sets were available for the northern stock: i.e., (1) biomass data from Fridtjof Nansen acoustic surveys from Morocco, Mauritania, and Senegal between 1995 and 2015 (Lakhnigue *et al*. 2019; Figure 7); and (2) catch data from industrial and artisanal fleets (Moroccan, Russian Federation, Ukrainian and others, European Union, Mauritanian, Senegalese, and Gambian) exploiting the stock in the region

[1] https://www.fishbase.ca/summary/Mugil-cephalus.html
[2] https://www.fishbase.ca/summary/Sardinella-aurita.html

(FAO 2016, Table 3.2.1b), and (3)fishing effort of these fleets on mixed sardinella fisheries (FAO 2016, Table 3.2.2). The average CPUE trend for the period 1990-2014 (Table 5) from these data was obtained using a software based on the method by Winker *et al.* (2020). The catch data suggested that an analysis for the period 1982-2016 could be performed, with a low depletion (B_{1982}/k=0.6-1.0) at the start of the time series being suggested by the CPUE trend.

There is no long-term time series of CPUE specific for the southern stock because it is caught with other sardinella in the Gulf of Guinea. However, FAO (2019a, Table 2.3.1c) presents CPUE data for *Sardinella* spp. from the Guinea-Bissau, Sierra Leone, and Liberian industrial and artisanal trawl fleets. The average CPUE trend for the period 1990-2012 (Table 5) was obtained using the method of Winker *et al.* (2020). Catch data heuristics suggested an analysis for the period 1970-2016, with the average CPUE trend used to set the intermediate biomass window B_{1996}/k at 0.1-0.4. The FishBase estimate of resilience (see Table 1) for this species was based on 3 life-history parameters and the r range was based on 6 stock assessments.[1]

Our assessment of the northern stock of Madeiran sardinella (*Sardinella maderensis*) off Mauritania, Senegal, and of the southern stock off Gambia Guinea-Bissau, Guinea, and Sierra Leone led us to conclude that they are overfished, with B/B_{MSY} = 0.74, and 0.79, respectively (see Table 6).

Sardina pilchardus

The European pilchard, also known as *sardina* in Arabic or *sardine* in French, is a coastal pelagic species forming schools commonly at depths of 25-55 m at daytime and 10-35 m at night and may extend to a maximum depth of 100 m (Whitehead 1985). It spans the Northeast Atlantic from the North Sea south to Senegal (Gorée) and is also present in the Mediterranean and the Sea of Marmara and the Black Sea (Whitehead 1985). There is one stock in the Saharan and Sahelian Upwelling marine ecoregion covering Mauritania, The Gambia, and Senegal.

Time series of relative abundance data were available for: (1) Moroccan, European, Gambian and Senegalese pelagic trawl fleets adapted from catch and effort data in Tables 2.2.1a and 2.2.1b of FAO (2016); (2) the CPUE of Moroccan purse seine fleets adapted from INRH/DP (2017; Figure 46 on p. 42); and (3) acoustic biomass estimates sampled by the R/V Dr. Fridtjof Nansen of Mauritanian and Senegambian stocks adapted from Lakhnigue *et al.* (2019; see Figure 7).

The average relative biomass trend expressed as CPUE was obtained using the method of Winker *et al.* (2020) and used here to inform the CMSY++ analysis. Catch data trend heuristics suggested an analysis for 1966-2016 with low depletion at the beginning of the time series (B_{1966}/k=0.6-1.0). An intermediate biomass window range of B_{2006}/k=0.2-0.6 was used following the CPUE trend. The FishBase resilience category (see Table 1) for this species was based on 3 life-history parameters, while the r-range was based on 18 stock assessments.[2]

FAO (2016) and Lakhnigue *et al.* (2019) assessed this stock as not fully exploited in the latter part of the time series. This assessment, diverging slightly, suggested that the European pilchard stock occurring off Mauritania, Senegal, and The Gambia is slightly overfished, with B/B_{MSY} = 0.88 (see Table 6).

Trachurus trachurus

The Atlantic horse mackerel is also known as *assatat* in Arabic (Hassaniya), *chinchard* in French, *chicharro* in Portuguese, *bologoui* in Susu, or *dîai* in Wolof. It is a coastal pelagic species forming large schools over sandy substrate found at the water column's surface to depths of over 1000 m but usually at depths of 100-200 m (FAO-FIGIS 2005). It is present in the Mediterranean Sea and the Eastern Atlantic from Norway to South Africa and along the coast to Maputo (Smith-Vaniz 1986b). Genetic evidence suggests one stock in the northeastern Atlantic up to Ghana (Healey *et al.* 2020), thus justifying the grouping in our analysis for

[1] https://www.fishbase.ca/summary/Sardinella-maderensis.html
[2] https://www.fishbase.ca/summary/Sardina-pilchardus.html

the Saharan Upwelling, Sahelian Upwelling and Gulf of Guinea West as one, i.e., for the whole Northwest African region.

The CMSY model does not seem to be applicable to the *Sea Around Us* reconstructed catch data from the three marine ecoregions covering our study area; therefore, the total catch data reported by Morocco, Mauritania, Senegal and the Gambia for 1990-2018 (adapted from FAO 2020a, Table 1.6.1) was used in this analysis. An average relative abundance trend for the period 1995-2015 was estimated using data from (1) acoustic biomass estimates sampled by the R/V Dr Fridtjof Nansen of Mauritanian and Senegambian stocks adapted from Lakhnigue *et al.* (2019, Figure 7); and (2) the Ram Legacy Stock Assessment Database (2018) and using the method of Winker *et al.* (2020). Although the catch data started in 1990, we opted to use catches for 1995-2018 to cover the same starting year as the relative biomass data. A low depletion was assumed at the start of the time series, i.e., B_{1995}/k range of 0.4-0.8. This was based on the decline in horse mackerel catches due to the temporary pull out, from 1990-1995, of East European fishing fleets mainly targeting horse mackerel in the region (Bah and Sidibé 2011; Ould Taleb Sidi *et al.* 2011). The intermediate B_{2006}/k range of 0.2-0.6 was based on the CPUE trend during that period (see Table 5). The FishBase resilience category (see Table 1) for this species was based on 4 life-history parameters, and the r-range was based on 11 stock assessments.[1]

The Atlantic horse mackerel (*Trachurus trachurus*) occurring off Mauritania, Senegal, The Gambia, Guinea-Bissau, Guinea, and Sierra Leone appears to be slightly overfished, B/B_{MSY} = 0.92 (see Table 6).

Trachurus trecae

The Cunene horse mackerel, also known as *carapau do Cunene* and *chicharro* in Portuguese, is benthopelagic, usually found at depths of 20-100 m (Schneider 1990). It occurs in the Eastern Atlantic from Morocco to Angola and sometimes to Namibia (Bianchi *et al.* 1999). We consider here one stock of the Cunene horse mackerel for the whole of Northwest Africa.

Similar to the Atlantic horse mackerel, the reconstructed catch data was not used for this analysis. Instead, the total catch data reported by Morocco, Mauritania, Senegal, and the Gambia for 1990-2018, adapted from FAO (2020a, Table 1.6.1), was used. We obtained an average relative abundance trend (1991-2015) for this stock from (1) acoustic biomass estimates sampled by the R/V Dr Fridtjof Nansen of Mauritanian and Senegambian stocks (adapted from Lakhnigue *et al.* 2019, Figure 7); and (2) the Ram Legacy Stock Assessment Database (2018), using the method of Winker *et al.* (2020). Similar to the Atlantic horse mackerel, East European fleets targeting this stock retracted from the subregion in 1990-1995 (see Bah and Sidibé 2011; Ould Taleb Sidi *et al.* 2011), which would have translated to a decrease in fishing pressure, resulting in a B_{1990}/k range of 0.2-0.6. In 2006, Jalloh and Seisay (2011, Table 2) estimated that the stock was at 56% of biomass at F = 0.1 with F/F_{MSY} = 0.98 (fully exploited; see Table 4), which translates to the B_{2006}/k range of 0.2-0.6 used as intermediate biomass prior in this analysis (see Table 5). The FishBase resilience category (see Table 1) was based on one value of the K parameter and the r-range was based on one stock assessment.[2]

Cunene horse mackerel (*Trachurus trecae*) occurring off Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Sierra Leone was assessed as healthy, with B/B_{MSY} = 1.1 (see Table 6); this result was unexpected and is discussed further below.

[1] https://www.fishbase.ca/summary/Trachurus-trachurus.html
[2] https://www.fishbase.ca/summary/Trachurus-trecae.html

Overall assessment

Our key results (Table 6; Figures 6A and 6B), which summarize the status of the 14 small pelagic stocks assessed here, suggest that overfishing is widespread in Northwestern Africa. This result is not new. Indeed, our results largely confirm those of previous authors, particularly to the FAO-led stock assessments summarized in Table 4, whose stock status evaluation matches ours when one considers different status definitions and their wording (Table 7). Indeed, a substantial discrepancy occurs only in Cunene horse mackerel (*Trachurus trecae*), which we evaluated as 'healthy' (see Table 6); while the FAO-led assessment, perhaps based on better data, concluded that it was 'overexploited' (Table 4).

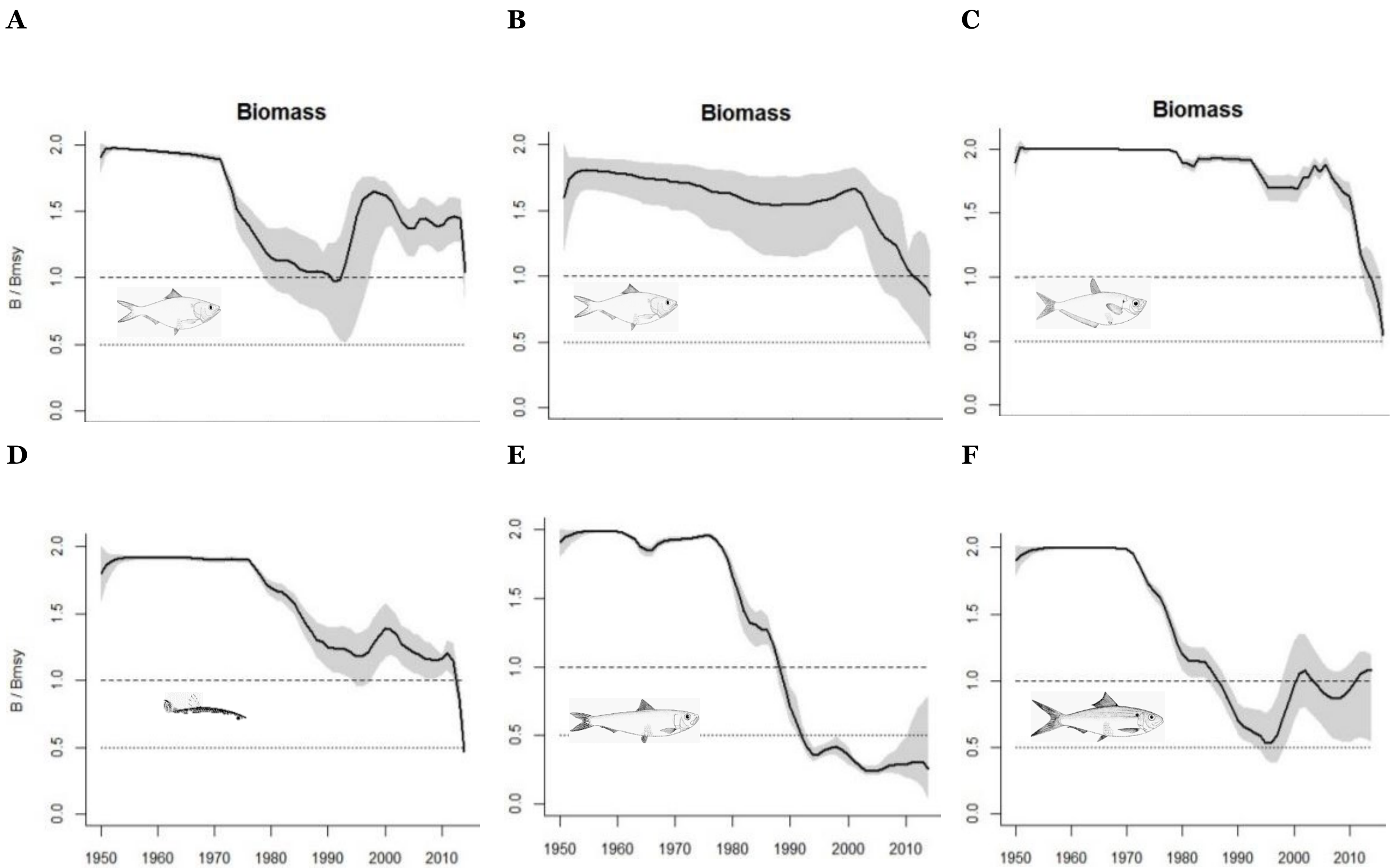

Figure 6A. Results of the CMSY analyses based on *Sea Around Us* reconstructed catch time series for 1950-2016 for non-straddling stocks in 3 marine ecoregions (see Table 6 for numerical results): (A) *Ethmalosa fimbriata* in the Sahelian Upwelling, (B) *Ethmalosa fimbriata* in the Gulf of Guinea West, (C) *Ilisha africana* in the Gulf of Guinea West, (D) *Mugil cephalus* in the Sahelian Upwelling, (E) *Sardinella aurita* in the Gulf of Guinea West, (F) *Sardinella maderensis* in the Gulf of Guinea West.

Table 7. Correspondence of terms used to assess the status of exploited fish stocks

FAO	***Sea Around Us***
Not fully exploited	$B \geq B_{MSY}$ (Healthy)
Fully exploited	$0.8*B_{MSY} \leq B < 1.0*B_{MSY}$ (Slightly overfished)
Fully exploited	$0.5*B_{MSY} \leq B < 0.8*B_{MSY}$ (Overfished)
Overexploited	$0.2*B_{MSY} \leq B < 0.5*B_{MSY}$ (Grossly overfished)
Overexploited	$B < 0.1*k$ or $B < 0.2*B_{MSY}$ (Collapsed)

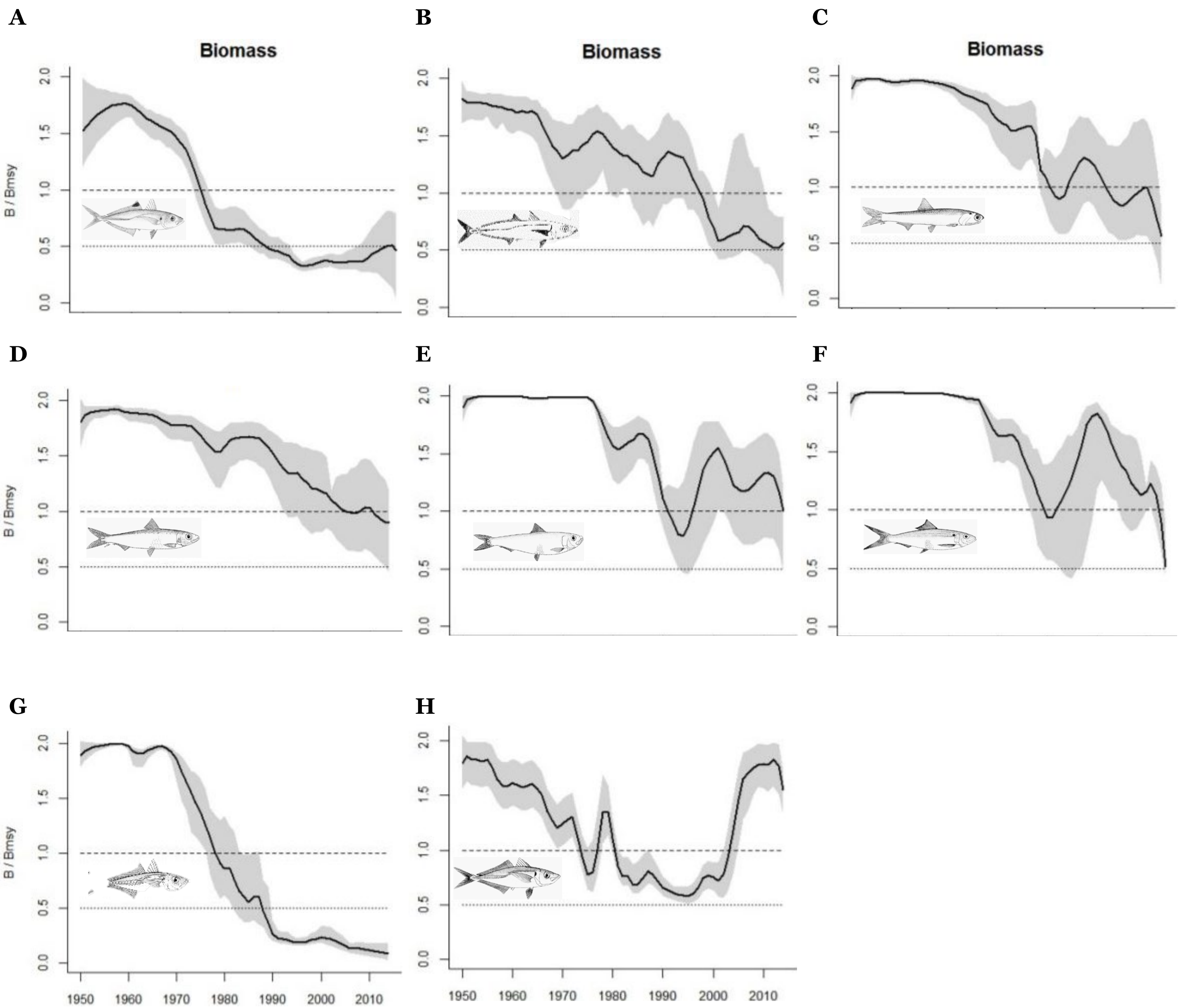

Figure 6B. Results of the CMSY analyses based on *Sea Around Us* reconstructed catch time series for 1950-2016 for straddling stocks in the 3 marine ecoregions (see Table 6 for numerical results): (A) *Caranx rhonchus* in North Western Africa, (B) *Decapterus macarellus* in the Eastern Central Atlantic, (C) *Engraulis encrasicolus* in Western Africa, (D) *Sardina pilchardus* in the Saharan Upwelling and the Sahelian Upwelling, (E) *Sardinella aurita* in the Saharan Upwelling and the Sahelian Upwelling, (F) *Sardinella maderensis*, (G) *Trachurus trachurus* in North Western Africa, (H) *Trachurus trecae* in Western Africa.

This confirms that the CMSY methods, when used with reliable catch time series, particularly when combined with CPUE and other ancillary data and priors from a length-based method, such as LBB, can quickly provide a credible stock assessment.

Thus, we encourage our colleagues in Northwest Africa and elsewhere to use the CMSY method, especially its latest versions (CMSY++), which resolve various issues noted by users.

Conclusions

We conclude this contribution with the slightly modified excerpts from the comments by Pauly (2019a, 2019b) on a major paper on fish in human nutrition by Hicks *et al.* (2019).

Eating fish is good for us. Fish are a source of micronutrients that help to prevent nutrient-deficiency diseases, which are a leading cause of infant deaths worldwide. Determining whether the consumption of locally caught fish could reduce the incidence of nutrient-deficiency diseases in countries particularly affected by this problem requires having access to the relevant data. Writing in *Nature*, Hicks *et al.* (2019) report their assessment of the nutritional content of 367 species of fish. For 43 countries, the authors mapped the relationship between the fish-derived nutrients available from fisheries' catches and the prevalence of nutrient-deficiency diseases in communities living within 100 kilometres of the coast. They found that most maritime countries, including developing countries would be sufficient to meet the key micronutrient needs of their populations.

For example, more than 75 % of the population in Namibia is at risk of calcium deficiency, even though enough fish is caught there to remedy this situation. In such cases, ensuring that even a fraction of a country's total fish catch is retained for local consumption could have a substantial impact on public health. This is particularly true for children under five years old, during a crucial stage of their development when micronutrient deficiencies have a severe effect. For 22 of the countries that Hicks *et al.* (2019) studied, 20 % or less of the fish caught could provide enough key micro- nutrients to meet the needs of all children under five years old.

Not only do nutrient shortages harm public health, but this problem has a knock-on effect of lowering gross domestic product. It might be supposed, then, that the governments of developing countries in the tropics – along with international development organizations or institutions such as the United Nations – would be doing everything possible to encourage the domestic consumption of fish caught in the EEZs of these countries. However, most economic-development policies, including those of these countries themselves, are geared towards promoting fish exports to match the insatiable demand for fish in the markets of high-income Western countries and East Asia (Swartz *et al.* 2010).

What are now the EEZs of economically developed countries were overfished long before overfishing began to occur in other countries. For example, the combined fisheries' catch in the North Atlantic peaked in 1975, and the world's catch peaked in 1996 (Pauly and Zeller 2016). The catch limits placed on overfished regions has led such economically developed countries on a quest to obtain their fish from other sources. These days, much of the haul in many parts of the developing world is either caught by local fishermen and exported, or taken by foreign fleets – which, by paying a nominal fee to access the EEZs of developing countries, catch fish for their own markets.

Such actions contribute to the scarcity of seafood and thus of micronutrients in many developing countries. This problem is perhaps greatest for countries in Northwest Africa. There, fishing by fleets from the European Union, Russia and China – and high fish exports to the EU – have led to resource decline and price increases that have made fish increasingly inaccessible to local consumers (Thiao *et al.* 2018). In Senegal, one of the countries studied by Hicks *et al.* (2019), sardinella is a staple food. A 2016 documentary film called *An Ocean Mystery: The Missing Catch* (see go.nature.com/2kyjv51) shows sardinella being smoked, dried and hand processed by Senegalese women and then trucked to the interior of the country, where these fish are the only affordable main source of micronutrients and animal protein. The leader of these workers emphasized in an interview in the documentary that it would be a catastrophe if the sardinella supply was interrupted, because they would have no fish to process.

Since then, this feared catastrophe has begun to happen. Despite much local consternation, more than 40 industrial fish- processing plants have been built, mainly by Chinese enterprises, along the coast of Senegal (see go.nature.com/2kva8bu) and neighbouring countries (see go.nature.com/2jtmcjq). These plants process sardinella and other small pelagic fish into fishmeal. Many of the local fisheries, which had traditionally supplied the regional markets with sardinella for human consumption, now instead supply the fishmeal plants, a process also noted in the Gambia by Sidibeh, *et al*. (2020, this vol.). These factories export their product mainly to China, which is the world's largest fishmeal importer, and it is commonly used there to feed farmed fish.

Thoughtful consumers in rich countries often insist that they eat fish certified as sustainably caught. This nebulous term often implies a hope that such fish are somehow being managed to ensure the continuation of an abundant supply. This contribution, and the report from which it is a part shows that this is not the case. These consumers also believe that farmed fish, e.g., salmon, contribute to sustainability, because it is widely thought that fish farming relieves pressure on capture fisheries. However, using sardinella to make fishmeal for farmed fish does not reduce the pressure on wild fish. Rather, it deprives people in the developing world, especially in Northwest Africa of previously affordable, nutritious local fish – to aid the production of costly farmed fish that is mainly consumed in high-income countries.

The above issues are not part of 'stock assessment; they are, however, part of what must be considered when managing fisheries.

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