A PRELIMINARY STOCK ASSESSMENT FOR THE SHORTFIN MAKO SHARK IN THE INDIAN OCEAN USING DATA-LIMITED APPROACHES

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SUMMARY

Despite its importance as a by-catch species and high biological vulnerability, there are currently no quantitative stock assessments for the shortfin mako, Isurus oxyrinchus, in the Indian Ocean. A quantitative stock assessment has been planned by the IOTC-WPEB for 2020. The aim of this paper is to provide a preliminary stock assessment and status for this stock, namely by providing 1) a catch series reconstruction between 2917-2015, 2) standardized CPUEs for EU longline fleets (Spain and Portugal), 3) estimation of a prior distribution for intrinsic growth rate (r) from demographic models, and 4) provide preliminary stock status using data-limited methods. Both a catch-only model (CMSY) and a Bayesian Schaefer production model were tested. The preliminary results indicate that the exploitation rate exceeded msy levels since the 1990s, with current F estimated to be well above Fmsy (F2015/Fmsy = 2.57). The relative biomass (B/Bmsy) is predicted to have had a continuously decreasing trend over time, and is estimated to be currently (B2015/Bmsy) close to 1. This indicates that currently the shortfin mako in the Indian Ocean is subject to overfishing but not overfished; however with trajectories showing consistent trends towards the overfished and subject to overfishing status. A reduction to fishing mortality levels observed during the early 1990s (around 3,000t) would likely be sustainable. However, and given the levels of uncertainty in the estimations, using the lower 95% confidence limit of MSY (1,570t) could serve as a more conservative guidance for total allowable catches. Due to the preliminary nature of this work and considerable amount of uncertainty in the estimations, management advice at this stage is not clear. However, this work it could serve as a baseline for more robust and complete analysis in the 2020 SMA IOTC stock assessment.

KEYWORDS: Data-limited, shortfin mako shark, stock assessment, stock status, Indian Ocean, pelagic longline fisheries.

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1. Introduction

The shortfin mako (*Isurus oxyrinchus*) is a highly migratory species found in tropical and temperate waters worldwide (Compagno, 2001). As with other pelagic shark species, *I. oxyrinchus* is commonly caught as bycatch by pelagic fisheries; it is the second most common shark species in these fisheries (Mejuto et al., 2009). Contrary to other shark species, shortfin makos are usually retained for their valuable meat and fins (Compagno, 2001). Ecological risk assessment conducted in Atlantic, Indian and Pacific Oceans considered the shortfin mako as one of the most vulnerable species due to its high susceptibility and low productivity (Murua et al., 2012; Cortés et al., 2015; Griffiths et al., 2017). Shortfin makos are the second most captured shark species by the EU longline fleets, after the blue shark.

Despite its importance as by-catch species and high vulnerability, catches in the Indian Ocean are considered to be underreported and/or can be reported in aggregated form (e.g. fleets reporting mako, which can include both shortfin and longfin makos). Additionally, few data on discards and size composition is available for the Indian Ocean. Regarding life history traits, there is information on age and growth, including a von Bertalanffy growth equation and longevity estimates, and on reproductive biology.

In regard to other oceans stock status and advice, a quantitative stock assessment was performed in the Atlantic Ocean in 2017 by ICCAT. The assessment results for the North Atlantic showed that biomass was bellow biomass at maximum sustainable yield (MSY) and fishing effort was well above the fishing effort at MSY (Anon., 2017). For the South Atlantic, there is high uncertainty in model estimations; however it was not possible to rule out that in recent years the stock may have been overfished and suffering overfishing (Anon., 2017).

Currently, no stock status information is available for shortfin mako in the IOTC area; also so far few indicators of stock abundance have been provided. Specifically, to this date only Japanese (Kimoto et al., 2011) and EU.Portugal (Coelho et al., 2013a; Coelho et al., 2017) have provided standardized catch-per-unit-of-effort (CPUE) for shortfin makos from those fleets. Both the Japanese and Portuguese series present a decrease in the first years of the series and an increase in abundance in the most recent years.

At present the main key obstacles preventing the quantitative scientific advice of shortfin mako stock status in the Indian Ocean are: 1) incomplete catch information, 2) limited availability of abundance trends indices (e.g. standardized CPUEs) and 3) limited of information of the composition of the catches (mainly length frequency distribution).

A quantitative stock assessment has been planned by the Working Party on Ecosystems and Bycatch (WPEB) for shortfin mako in the Indian Ocean by 2020 (IOTC, 2017). As such, this paper aims to present a preliminary stock status of this species for the Indian Ocean using a data limited assessment method. The following specific objectives and steps were followed: 1) reconstructing shortfin mako catch time series for the period 1971-2015; 2) estimating catch-per-unit-effort time series based on the longline fisheries that target swordfish and have bycatches of shortfin mako (EU fleets - Portugal and Spain), 3) estimating a probability density distribution for shortfin mako intrinsic population growth rate (*r*) for use as a prior in the assessment model, and 4) implementing a feasible preliminary stock assessment model for the Indian Ocean shortfin mako, in this case based on estimated catches, resilience and qualitative stock status information.

2. Material and methods

2.1. Catch reconstruction

Catches were reconstructed between 1971 and 2015 using a ratio based method. This method was originally developed for the EUPOA - EU Plan of Action for sharks (see Murua et al., 2013; Coelho et al., 2018). It has been since then already applied and used as sensitivity scenarios during the latest (2017) stock assessments of blue shark in IOTC (Coelho and Rosa, 2017a) and shortfin mako in ICCAT (Coelho and Rosa, 2017b).

2.2. Catch per unit of effort (CPUE) standardization

2.2.1. Portuguese CPUE series standardization

A continuous effort over the last years has been made by the Portuguese Institute for the Ocean and Atmosphere (IPMA) to collect current and historical catch and effort data from the Portuguese longliners targeting swordfish in the Indian Ocean. This includes information on the catches, fishing effort (number of sets or hooks per set) and geographical location (integrated from VMS data). Such data mining effort has allowed IPMA to recover most of the time series for the Portuguese pelagic longline fleet operating in Indian Ocean (**Table 1**).

For the CPUE analysis, this operational level data from logbooks was used, with the catch data referring to the total (round) weight of shortfin makos captured per fishing set. The available catch data started in 1998 and was available until 2016. However, the first 2 years of the series (1998 and 1999) were not used for the model because there was more limited information in those initial years of the fisheries. For the CPUE standardization, the response variable considered was catch per unit of effort (CPUE), measured as biomass of live fish (kg) per 1000 hooks deployed. The standardized CPUEs were estimated with Generalized Linear Mixed Models (GLMMs).

Table 1. Number of fishing sets with catch, effort (hooks) and location information carried out by the Portuguese pelagic longline fleet in the Indian Ocean between 1998 and 2016. The percentage of sets per year analyzed for this paper is also indicated. Note

that the 2 first years of the series (1998 and 1999) were not used for the CPUE standardization analysis due to lower effort in the Indian Ocean.

Year	Sets (n)	Sets with effort (Hooks)	Sets with locations (VMS)	Sets used for analysis (%)
1998	113	113	113	100.0
1999	147	147	147	100.0
2000	275	275	275	100.0
2001	631	631	631	100.0
2002	687	687	647	94.2
2003	575	575	575	100.0
2004	370	370	370	100.0
2005	143	143	143	100.0
2006	1801	1801	1801	100.0
2007	1325	1325	1325	100.0
2008	238	238	238	100.0
2009	482	482	482	100.0
2010	457	457	457	100.0
2011	633	633	633	100.0
2012	516	516	516	100.0
2013	1312	1312	1312	100.0
2014	863	863	863	100.0
2015	1302	1302	1302	100.0
2016	1445	1445	1445	100.0
Total	**13315**	**13315**	**13275**	**99.7**

Coelho et al. (2014) has previously tested 10 sensitivity runs in blue shark CPUE standardization models, including sensitivities to the model type, the use of ratio factor and the definition of the area effects. The base case used for the present work on shortfin mako was based on the best model approaches selected in that work. Additionally, Coelho et al. (2016) tested targeting effects to this fleet by using ratios versus cluster analysis, demonstrating that both had very similar behaviours in this particular fleet (fleet targeting mainly swordfish -SWO- but with sharks, mainly blue shark as a secondary target).

As the shortfin mako shark is a bycatch from the fishery, there were considerable trips or sub-trips with zero catches that results in a response variable of CPUE=0. As these zeros can cause mathematical problems for fitting the models, a Tweedie model was used, as described in Coelho et al. (2013b) for the shortfin mako SMA CPUE standardization for the Portuguese fleet in the Atlantic Ocean.

The tweedie model uses an approach in which only one model is fitted to the data, with that model handling the mixture of continuous positive values with a discrete mass of zeros. The tweedie distribution is part of the exponential family of distributions, and is defined by a mean (μ) and a variance (φμp), in which φ is the dispersion parameter and p is an index parameter. In this study, the index parameter (p-index) was calculated by maximum likelihood estimation (MLE).

Based on the sensitivities and tests reported by Coelho et al. (2014), the covariates considered and tested in the base case models for this work were:

- Year: analyzed between 2000 and 2016;
- Quarter of the year: 4 categories: 1 = January to March, 2 = April to June, 3 = July to September, 4 = October to December;
- Area: Using a GLM Tree area stratification based on Ichinokawa & Brodziak (2010) approach;
- Ratio: based on the SWO/(SWO+blue shark) ratio of captures;
- Interactions: first order interactions were tested and would be used if significant with the AIC criteria;

Interactions were considered and tested in the models. Specifically, interactions not involving the year factor were considered as fixed factors in the GLM, while interactions involving the year factor were considered as random variables within GLMMs.

The significance of the explanatory variables was assessed with likelihood ratio tests comparing each univariate model to the null model (considering a significance level of 5%), and by analyzing the deviance explained by each covariate. Goodness-of-fit and model comparison was carried out with the Akaike Information Criteria (AIC). Model validation was carried out with a residual analysis. The final estimated indexes of abundance were calculated by Least Square Means (marginal means), that for comparison purposes were scaled by the mean standardized CPUE in the time series.

2.2.2. Spanish CPUE series standardization

Data for the analysis was compiled from the logbooks of the Spanish pelagic longline fishery operating in the Indian Ocean (FAO IO divisions 51, Western Indian Ocean; 58 Indian Ocean, Antarctic and Southern; 57, Eastern Indian Ocean) for the period 2006-2016 (with the exception of year 2008, for which there was no information available). The information, recorded on a trip basis, included vessel identification, date and geographical position by fishing operation, and catch by species in kg.

Data inspection basically entailed the elimination of incomplete and erroneous records. Whenever possible, incorrect measurement units were corrected. As a result, approximately one per cent (1%) of the records available for the period 2006-2016 was discarded for later analysis. A total of 624 fishing trips for the period 2006-2016 were available for further analysis.

Based on the estimated annual percentages of shortfin mako fishing sets with zero catch (**Table 2**) and the observed skewed distribution of shortfin mako positive catches, a Generalized Additive Mixed Model (GAMM) assuming a Tweedie distributed error was implemented for CPUE standardization (Winker et al., 2014, Ono et al., 2015; see description above in the Portuguese CPUE standardization).

Table 2. Estimated annual percentages of SMA fishing sets with zero catch.

Year	Zero catch (%)
2006	56.72
2007	54.93
2008	NA
2009	44.79
2010	51.70
2011	40.16
2012	44.04
2013	37.04
2014	19.62
2015	28.57
2016	56.29

The final model formulation included as explanatory variables year, month, and a random intercept for vessel.

2.3. Demographic analysis

A stochastic population dynamics model (demographic analysis) using age-based Leslie Matrices was carried out to estimate the population intrinsic growth rate (r) (Caswell, 2001). Since only females produce off-spring, the demographic analysis was carried out exclusively for the female component of the population (Simpfendorfer, 2004). The age-structured model conceived was a pre-breeding survey model, where reproduction and natality take place first, followed by the probability of survivorship-at-age. Thus, the age-specific fecundity values of the Leslie matrix (Fx) were calculated as the products of the age-specific fertilities (mx) and the first-year survivorship (s0): Fx=s0*mx. In terms of survivorship, the age-specific survivorship was estimated based on several indirect life history equations, specifically Pauly (1980), Hoenig (1983), Jensen (1996), Peterson and Wroblewski (1984), Chen and Watanabe (1989).

Four different scenarios were analyzed and compared (**Table 3**). These scenarios accounted for different information on life history parameters available from the literature (Barreto et al., 2016; Rosa et al., 2017) and different possible alternatives that can be used to estimate fecundity (either a 2 or 3-year reproductive cycle, still uncertain for the species).

Uncertainty in the analysis was introduced in the survivorship and fecundity parameters. Uncertainty in the survivorship parameters was introduced by generating age-specific random survivorship values from a uniform distribution with support defined between the minimum and maximum empirical age-specific estimates. For the fecundity parameters, uncertainty was considered by generating random age-specific fertilities based on a normal distribution, with the expected values and standard deviations based on the fertility-at-age values. Each scenario was simulated using 10000 Monte Carlo replicates varying each input parameter (survivorship and fecundity) based on the previously assumed distributions. The resulting 10000 Leslie matrices were analysed, and the distributions of the output parameters summarized as the mean r values and the corresponding 95% confidence intervals (0.025 and 0.975 quantiles).

Table 3. Biological data inputs for the demographic analysis, assuming different scenarios in terms of the species biology.

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**References**
	Barreto et al., 2016		**Rosa et al., 2017**		
Theoretical maximum length (L_{inf}, cm)	407.56		350.3		
Growth coefficient (k, year^{-1})	0.04		0.064		
Theoretical age at length zero (t_0, years)	-7.08		-3.09		
Lifespan (years)	32				Natanson et al., 2006
Reproductive cycle (years)	2	3	2	3	Mollet et al., 2000
Intercept of maturity ogive	-53.14				
Slope of maturity ogive	19.46				
Sex ratio at birth	1:1				
Scalar coefficient of litter size on TL	0.81				
Power coefficient of litter size on TL	2.346				
Scalar coefficient of weight on length	0.0000349				Romanov & Romanova, 2009
Power coefficient of weight on length	2.76544				
Slope of TL to FL relationship	0.929				Kohler et al., 1995
Intercept of TL to FL relationship	-1.7101				

2.4. Assessment model

Considering the information available, effort was focused on the implementation of the CMSY model developed by Froese et al. (2017).

In essence, this model implements a stock reduction analysis using default priors for the intrinsic rate of population growth (r), based on resilience; for the carrying capacity or unexploited stock size k, based on maximum observed catch and estimated priors for r; and start, intermediate, and final year depletion levels (B/k), based on a set of simple rules. It allows for the inclusion of priors for the input parameters (r, k and depletion) based on expert knowledge or estimated by any other feasible method. The stock reduction analysis uses a Schaefer biomass dynamic model and an algorithm for identifying feasible r-k combinations to estimate biological and management quantities (r, K, MSY, BMSY, FMSY) as well as time series of biomass, fishing mortality, and stock status benchmarks (B/BMSY, F/FMSY).

It is worth noting that in its current version CMSY addresses the overestimation of productivity at very low stock sizes (general shortcoming of production models) by implementing a linear decline of surplus production when biomass falls below 1/4k.

2.4.1. Input data and model configuration

Estimated catches for the period 1971 to 2015 were used. Although CMSY is primarily a catch-only assessment method, the package also offers the possibility to fit a Bayesian surplus production model (Schaefer) if abundance indices are available. The two abundance indices available for shortfin mako, specifically the Portuguese and Spanish longline indexes, were used.

2.4.2. Range of parameters explored

The largest and smallest r values from the demographic analysis (0.008-0.048) were used to define the range of r values explored in CMSY. In addition to this, CMSY was also run using the default approach, in which the resilience value available on FishBase is used to define the range of r. For shortfin mako, resilience is estimated to be very low (Froese & Pauly, 2015), which for CMSY defaults corresponds to values of r in the range 0.015-0.100 (see Froese et al., 2017), a little wider and centred on higher values than the first option.

As regards the range of depletion rates (B/k), at the start of the time series (1971), the stock is believed to be already lightly exploited. An initial depletion rate (B/k) of 0.7-0.9 was therefore used. In order not to constrain too much the estimated stock trajectory, a wider range, between 0.2 and 0.7, was used for the final year (2015) depletion rate.

By default, CMSY uses an intermediate depletion rate (10 years before the end of the available time series) with values in the range 0.2-0.6. Preliminary runs using this default option showed that this range is very restrictive. In order to give the model more freedom, a larger range was set (0.1-0.9, for year 2000).

Further model configuration involved both the choice of variance for the catch data (observation error), and variance of the process error. For both the default value was 0.1, which seemed considerable low (especially given that the catches were estimated by using a model); hence, higher values (0.2) were tested. This was found to have no effect on the output of CMSY.

3. Results

3.1. Catch reconstruction

There are differences of shortfin mako reported versus estimated catches along the entire time series, even when considering the reported catch of Isurus spp. In both series there is a steady increase until the early 1990's. In the reported time series the catches continue to increase until 2015, while in the estimated catches there is a rapid increase in the early 1990's followed by a steadily increase thereafter (**Figure 1**).

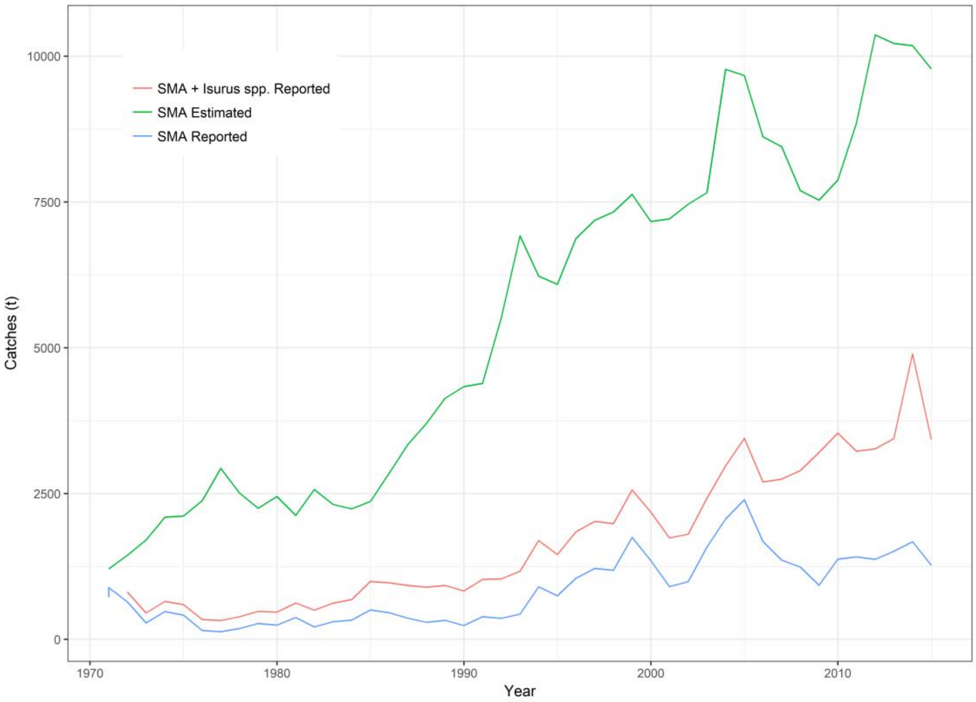

Figure 1. Time series of reported shortfin mako (SMA) and shortfin mako + reported catch of Isurus spp. and estimated shortfin mako catches, between 1971 and 2015, for the Indian Ocean.

3.2. Catch per unit of effort (CPUE) standardization

Two abundance indices were prepared and available for shortfin mako, based on the Portuguese and Spanish pelagic longline fleets (**Figure 2**). The series cover the period

2000-2016 and 2006-2016, respectively, and show globally an increasing trend over the last decade.

Figure 2. Shortfin mako scaled standardized CPUE series for Portugal (2000–2016) and Spain (2006-2016).

3.3. Demographic analysis

Using different biological scenarios (see **Table 3**) had an effect on the estimated r, both between growth models and periodicity of the reproductive cycle (**Figure 3**). Considering the different growth parameters, Scenarios 1 and 2 had higher estimates of r (0.032 and 0.048, respectively) than scenarios 3 and 4 (0.008 and 0.025, respectively). When comparing between periodicity of the reproductive cycle, the scenarios with a 2-year cycle (Scenarios 1 and 3) estimated a higher r than scenarios with 3-year cycles (Scenarios 2 and 4).

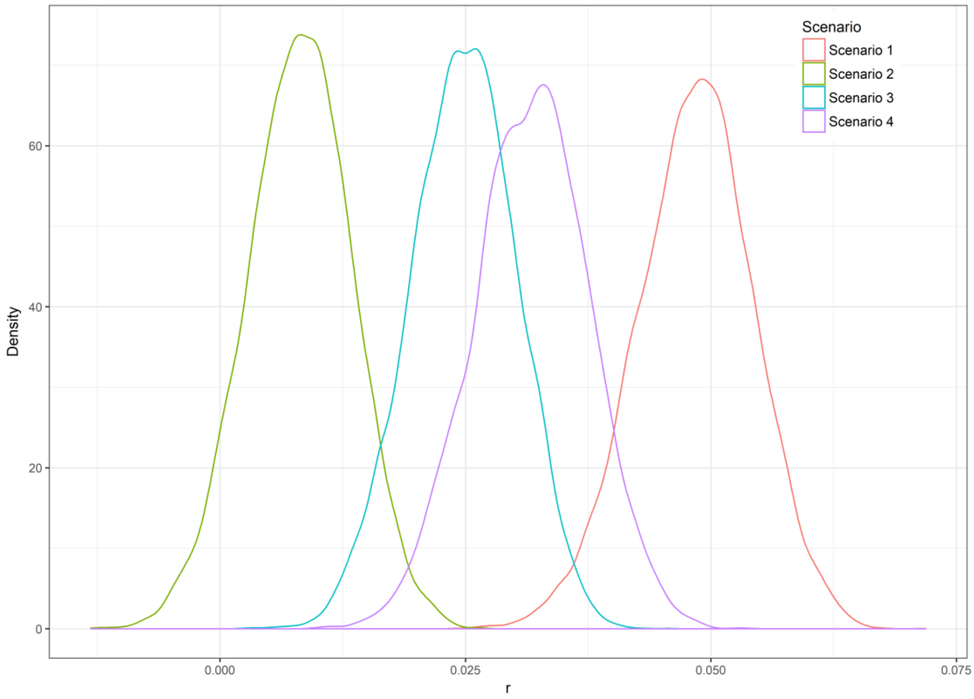

Figure 3. Plot of intrinsic rate of growth (r) estimates from stochastic demographic analysis for the different biological scenarios (see **Table 3**).

3.4. Assessment model

3.4.1. Influence of the choice of the prior on r

The two options tested for the prior on r did not do not fully overlap. As a result, the “best” r estimate using the Leslie model based range is lower than with the resilience based approach (0.031 and 0.062 respectively, **Figure 4**). The corresponding K values are 462 thousand tonnes (kt) and 309 kt respectively.

3.4.2. Output of the final CMSY configuration

The final configuration of the model included the Leslies based r prior since they provide a more realistic range of r value for this species than values taken from Fishbase, the expert knowledge based initial and final depletion rates and a broad range of depletion for the intermediate year (with a view to minimizing the impact in the CMSY results).

Final model configuration estimates of r, k and related quantities are given in **Table 4**.

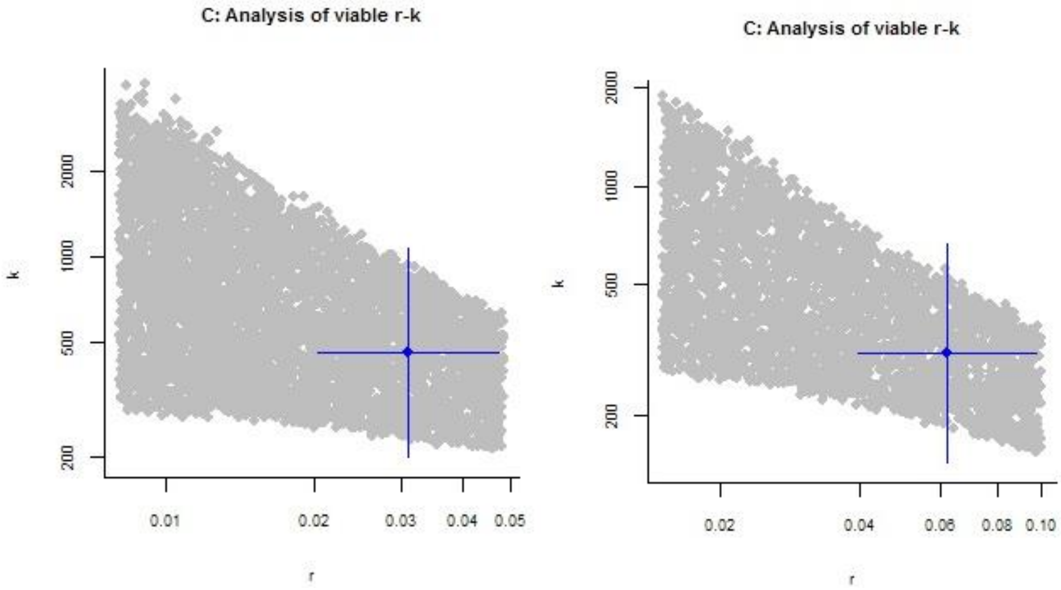

Figure 4. Viable r/K pairs (grey dots), and "best estimates" (and associated uncertainty), blue crosses, for the runs of CMSY using the Leslie based priors (0.008-0.048) on r (left) and the resilience based priors on r (0.015 – 0.1) (right).

Table 4. Model configuration estimates from CMSY.

Parameter	Estimate	95% CI
r	0.031	0.0203-0.0473
k	462 (1000 t)	199-1072 (1000 t)
MSY	3.58 (1000 t)	1.57-8.13 (1000 t)
Relative biomass last year (2015)	0.531 k	0.213-0.696
Exploitation F/(r/2) last year (2015)	2.57	

The stock is believed to have been at almost pristine state in 1971 (B/k around 0.8), started declining in the 1990s to close to BMSY in 2015. The exploitation rate was low in the early years, increasing strongly since the early 1990s to a value of 2.6 times FMSY currently. Therefore, the results give the perception that the stock biomass is still above BMSY (stock is not overexploited), but the current fishing mortality is high, around 2.6 times higher than FMSY (stock is currently under over-exploitation)

When using the Bayesian Schaefer model (BSM), the two abundances indices available indicate an increasing stock, which is contradictory with the biomass trend calculated by CMSY. The BSM r estimates are lower than CMSY, with both surveys having an estimated r of 0.02 (CMSY r estimate is 0.031) and higher K (768 kt based on Portuguese survey and 936 kt based on the Spanish survey, against 462 for CMSY).

The estimated biomass from both BSMs is (following the variation in the indices used) increasing from a situation just under BMSY in the early 2000s to well above BMSY in 2015 (**Figure 5**). Exploitation rates are expected to be high (from both BSMs), well above FMSY, with no marked trend. For these models this stock is currently overexploited and under over-exploitation.

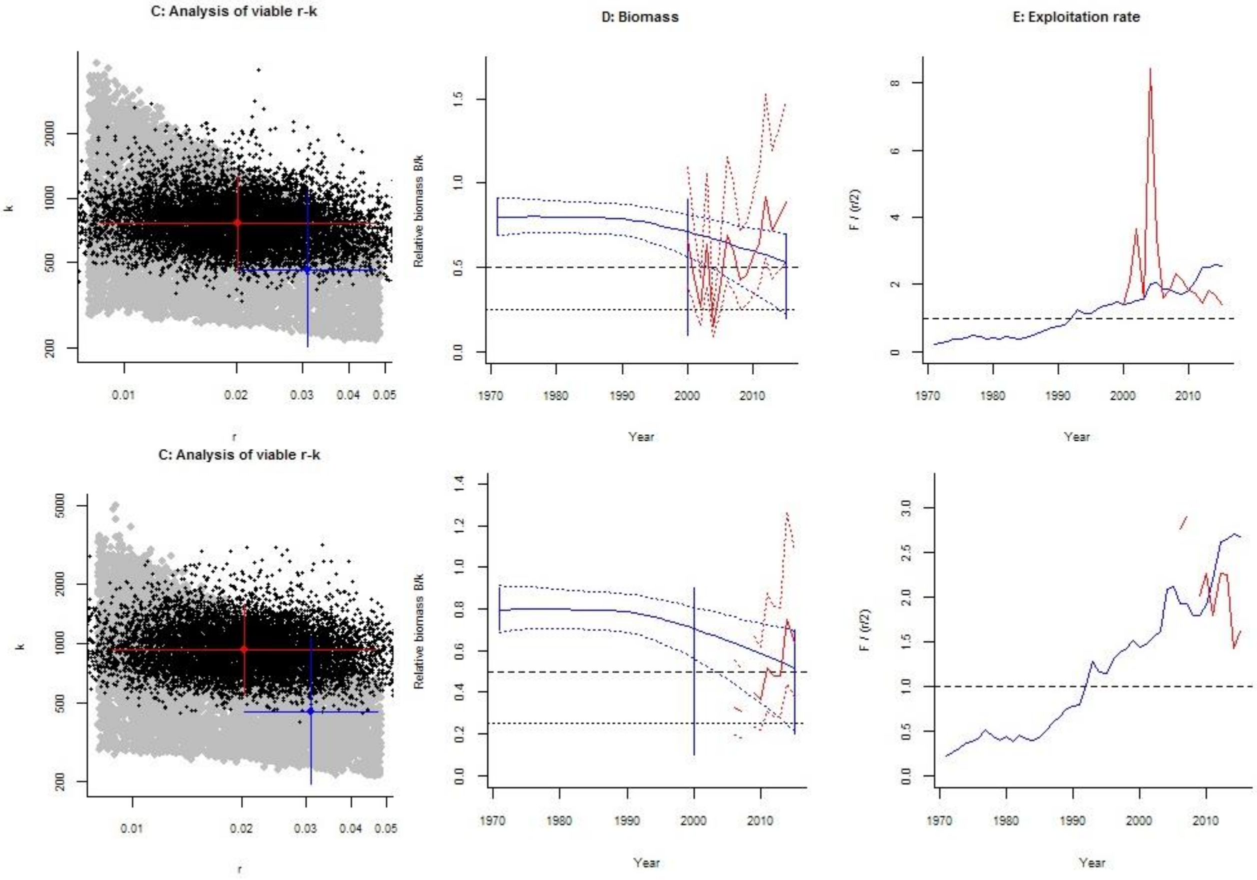

Figure 5. Output of the Bayesian Schaefer model using the Portuguese CPUE index (top) and the Spanish CPUE index (bottom). Panel C: comparison of the CMSY and Bayesian Schaefer estimates of r and K (blue and red respectively, with grey dots depicting the viable estimates from CMSY and the black dots depicting the distribution of the Bayesian estimates from the Bayesian Schaefer model); Panel D: estimated biomass (relative to K) and Panel E: exploitation rate from the CMSY run (blue) and the Bayesian model (red).

4. Discussion

4.1. Stock status and management recommendations

Regarding the conflicting trends in biomass between BSM and CMSY, preliminary stock status and management recommendations are given mainly based on the CMSY results. Catches exceeded maximum sustainable yield before the 1990’s, with an upward trend until the end of the reconstructed time series (**Figure 6**). As regards exploitation, it was below the MSY-level in the years before the early 1990’s; from then on, the exploitation increased beyond the levels compatible with maximum sustainable yield. The exploitation rate for year 2015 (last in the available time series) was predicted to be well above the MSY-level (F2015/FMSY = 2.57) with a wide margin of uncertainty around that prediction (**Figure 6**). CMSY predicts biomass above BMSY from the beginning of the time series with a decreasing trend until the end of the series. The estimation of current biomass (2015) to biomass at MSY was close to 1, with a considerable margin of uncertainty in the prediction (**Figure 6**). According to the CMSY predictions, at present the shortfin mako stock would be subjected to overfishing but not overfished, however with the trajectories showing consistent trends towards the overfished and subject to overfishing status (**Figure 6**).

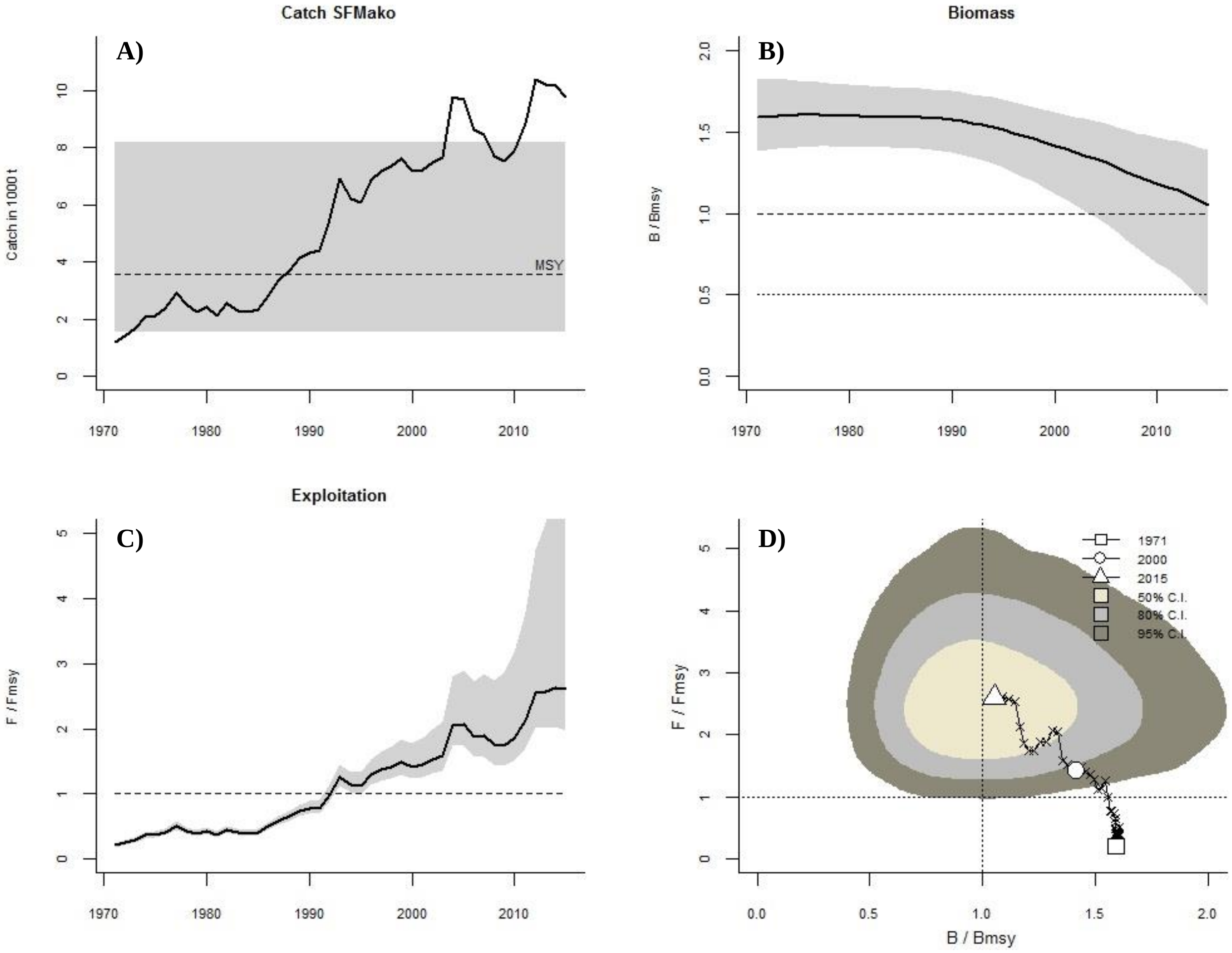

Figure 6. CMSY stock status results. A) Line represents reconstructed catch time series (1971-2015). Horizontal dashed line indicates MSY, and the shaded area indicates the confidence limits of MSY. B) Predicted biomass with confidence limits (shaded area). Horizontal dashed line indicates BMSY and the dotted line indicates 0.5BMSY. C)

Exploitation rate (solid line) and associated uncertainty (shaded area). Dashed horizontal line indicates exploitation compatible with MSY. D) Temporal evolution of biomass and exploitation relative to BMSY (vertical dashed line) and FMSY (horizontal dashed line), respectively. Bivariate experimental confidence intervals correspond to the last year in the available time series (2015).

4.2. Final remarks

Due to the considerable amount of uncertainty in the estimates, management advice is not clear from this preliminary work.

Recent fishing mortality levels appear to be likely in excess of FMSY. Fishing reduction to the levels observed during the early years in the 1990's would likely be sustainable. Precautionary management may restrict catches at levels observed in late 1980s and early 1990s (around 3000t) until additional information allows for a more detailed analysis. However, given the current level of uncertainty on the estimated reference points, the estimated lower 95% confidence limit of maximum sustainable yield (1570t) may serve as a more conservative guidance for total allowed catches. Management measures designed to reduce catch and effort directed at Indian Ocean shortfin mako should be implemented.

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