Investigation into the effects of catch time series estimations on stock assessment of Silky sharks (*Carcharhinus falciformis*) in the Indian Ocean

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Abstract

Reported catches of sharks to the IOTC are likely highly inaccurate due to insufficient species-specific reporting. This creates difficulties in conducting quantitative stock assessments in the region. Silky sharks are one of the most abundant shark species caught in Indian Ocean and are ranked as one of the most vulnerable species in the region, putting their populations at high risk of being overfished. Following the preliminary stock assessment of Indian Ocean silky sharks in 2018 (uncertain status), this study proposes novel estimated catch time series for silky sharks and investigates their effects on stock assessment results using the data-limited CMSY model. It was found that estimated values of resilience (r) and F-based statistics were considerably different when using different r categories. The two reconstructions varied most in k, MSY and B_{MSY}, while F_{MSY}, B/k, B/B_{MSY} and F remained relatively constant across all reconstructions within the same r categories. F/F_{MSY}, however, remained consistent across all scenarios. Overall, the input resilience category has a larger influence on the output of the model than the estimated catch time series. All 4 assessments showed that overfishing ($F/F_{MSY} > 1$) is occurring and that the stock is more likely to be overfished when a low resilience category is used, compared to very low. Therefore, adopting a precautionary approach and introducing specific management measures for silky sharks in the Indian Ocean is highly encouraged.

Keywords: elasmobranchs, resilience, CMSY, overfishing

1. Introduction

Shark catch data prior to 1970s is scarce and data reported to the IOTC prior to 2014 is thought to be inaccurate, incomplete and underestimates the quantity of actual shark catches due to lack of data recording and reporting (Clarke *et al.*, 2014; Murua *et al.*, 2013a). For catches that are reported, they likely do not represent total catch and are often not reported at the species level (Murua *et al.*, 2013a). This lack of species-specific catch data makes it extremely challenging to conduct quantitative stock assessments for shark species in the region.

Silky sharks are predominantly captured (as target or bycatch) in industrial and artisanal tuna fisheries throughout the Indian Ocean. They are estimated to be the second major species of shark caught in the Indian Ocean (Murua *et al.*, 2013a) and are valued for both their meat and fins (Clarke *et al.*, 2006; Blue Resources Trust pers. comms.). Catch trends of silky sharks in the Indian Ocean are almost entirely driven by catches reported by the Sri Lankan fleet (Herath & Maldeniya, 2013; IOTC, 2021; Murua *et al.*, 2013a; Murua *et al.*, 2018; Murua *et al.*, 2013b). While Sri Lanka appears to be the largest catcher of silky sharks in the Indian Ocean, they were the only CPC[1] that reported catches of silky sharks to the IOTC between 1986 and early 2010's. Other fleets may also have targeted fisheries for silky sharks or large volumes of silky shark bycatch, but have not been reported to the IOTC (IOTC, 2021). Since 2012, silky shark catches are mainly reported from gillnet fisheries from Pakistan, Sri Lanka, and Iran; representing 25%, 40%, and 35%, respectively (IOTC, 2021).

Biological parameters are reasonably well known for this species from other oceans (IOTC, 2016; IOTC, 2021), however biological information from the Indian Ocean is scarce. A Productivity-Susceptibility Analysis (PSA) as part of an Ecological Risk Assessment (ERA) (Murua *et al.*, 2018) found silky sharks in this region to be one of the most vulnerable species to overfishing for all gear types due to relatively low productivity and very high susceptibility. They ranked 2nd in vulnerability to longline fisheries and 5th in vulnerability to purse seine and gillnet fisheries. Their population has been reportedly declining in recent decades (Herath & Maldeniya, 2013) and their status was elevated from Near Threatened to Vulnerable on the IUCN Red List of Endangered Species, following an assessment in 2017 (Rigby *et al.*). Except for a preliminary assessment in 2018 (Ortiz de Urbina *et al.*), no stock assessments thus far have been carried out for silky sharks in the Indian Ocean and the stock status remains highly uncertain.

This study aimed to reconstruct new estimated catch time series to improve the accuracy of the stock assessment results using the CMSY model[2] developed by Froese *et al.* (2017). Ratio-based methods form the basis of several reconstructions of catch time series (Murua *et al.*, 2013a) and new methods are proposed to increase the accuracy of catch estimations. Stock assessments were carried out using the new catch time series reconstructions and the CMSY model. The results were compared to assess the effects of estimated catch time series on the stock status of silky sharks.

[1] CPC = IOTC Members and Cooperating Non-Contracting Parties
[2] This is an advanced version of the Froese & Martell 2013 model for Catch-MSY

2. Methods

2.1 *Reconstruction of silky shark catch time series*

Two novel catch time series were constructed using IOTC nominal catch data (publicly available on the IOTC website). Reconstructions for the catch time series of silky sharks caught in the Indian Ocean from 1971 to 2019 were carried out using ratio-based methods (Murua *et al*. 2013a). These methods estimate potential shark catches based on reported catch of target species, since this data is believed to have higher accuracy than reported shark catches (Murua *et al.,* 2013a). Assumed ratios of shark catch/catch of target species per gear group used in this paper were taken from Murua *et al. (*2013a*)* (Table 1).

Reconstruction 1 (R1): This calculated the proportions of silky sharks in relation to all sharks:

R1 = *target species catch*[3] ** (ratio of shark catch / target species per gear group) * (proportions of silky shark catch / total shark catch per gear group)*

Reconstruction 2 (R2):

The time series was separated into 2 parts, taking into account the influence of silky shark catch data reported by Sri Lanka:

Part 1 (P1): Reported silky shark data for Sri Lanka from 1971-2012[4]

Part 2 (P2): Estimation of silky shark catch for all other CPC fleets from 1971 to 2012 together with Sri Lanka data from 2013 to 2019:

P2 = *target species catch * (ratio of shark catch / target species per gear group) * (proportions of silky shark catch / total shark catch per gear group)*

Part 3: Final estimated catch time series = P1 + P2

For part 2 of this time series, the proportions of silky sharks to all shark catches are taken from the Ecological Risk Assessment from Murua *et al*. (2018) (Table 1).

[3] Target species in this study is defined as all tuna species under the IOTC management mandate
[4] Data until 2012 was used [IOTC–2016–WPDCS12–RE] since data collection improved due to the implementation of logbooks in 2012.

Table 1. Ratios (in tonnes) assumed for shark catches in relation to target species (Murua *et al.*, 2013a) and proportions of silky shark catch/all sharks for each gear group reported in the 2018 ERA by Murua *et al.*

Gear Group	Target Fishery	Ratio of shark catch/target species	Proportion of Silky shark catch/all shark catch
Baitboat	Major tunas	0.000	0.00
Gillnet Combined	Major tunas	2.000	0.05
Line	Major tunas	0.002	0.01
Longline	Major tunas	0.150	0.17
Purse Seine	Major tunas	0.002	0.07
Others	Major tunas	0.300	0.00

2.2 CMSY Model

The CMSY method developed by Froese *et al*. (2017) was implemented here to carry out an updated stock assessment using novel catch reconstructions. CMSY is a catch-based surplus production model that is beneficial when age-structured models are not feasible due to insufficient data, making it an ideal method for data-limited species. The model uses a stock reduction analysis that implements a Schaefer biomass dynamic model, built from the Schaefer production model (1954). Unlike regular biomass dynamic models that estimate productivity, CMSY can estimate the biomass of a stock through time based only on the productivity of a species and a time series of catches.

The CMSY model requires the following set of input data:

1. prior ranges for the intrinsic rate of population increase (r), also referred to as resilience here.
2. prior ranges for the carrying capacity of the stock (k)
3. prior ranges for depletion levels or biomass relative to the unexploited stock (B/k)

Using the Markovian chain Monte Carlo (MCMC) method, the model filters a range of r-k pairs, then finds the r-k pair with the best fit and uses these to estimate fisheries reference points, including estimated values for maximum sustainable yield (MSY), maximum rate of fishing mortality (F_{MSY}), biomass capable of producing MSY (B_{MSY}) as well as relative biomass (B/B_{MSY}), relative stock size (B/k) and exploitation (F/F_{MSY}).

2.3 Priors r and B/k for CMSY

Prior ranges for r and B/k required for input into the CMSY model were taken from those used in the preliminary silky shark stock assessment (Ortiz de Urbina *et al.*, 2018). The preliminary assessment and Fishbase (Froese & Pauly, 2015) both report silky sharks to have a resilience value of 0.06 which falls under default resilience categories of low and very low. Therefore, stock assessments were explored using both default resilience categories from Fishbase of low (r prior range of 0.05 to 0.5) as well as very low (r prior range of 0.015 to 0.1).

Prior ranges for B/k included 0.7-0.9 for the initial year of 1971, 0.1-0.9 for the intermediate year of 2000, and 0.2-0.7 for the final year of 2019.

Stock assessments were carried out for all reconstructions, using both r = low and r = very low, and results were compared to see how various catch time series affect the output of the model.

The 2019 CMSY model was used for all analyses in this study (R code for the model can be found in Froese *et al.*, 2017). Additionally, default values for observation (catch data) error and process error were used, corresponding to variance of 0.3 and 0.1, respectively.

3. Results

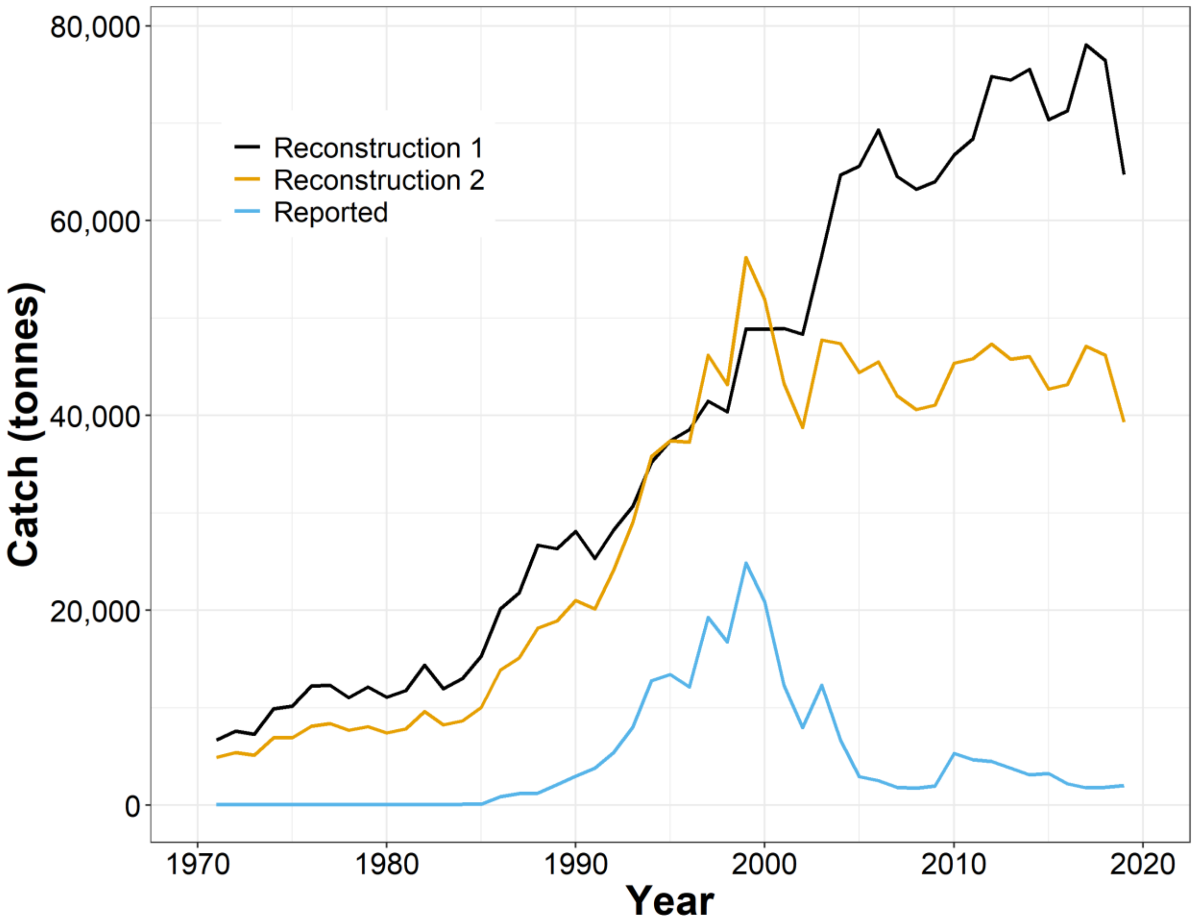

Figure 1. Reported and estimated catch time series of silky shark in the Indian Ocean between 1971-2019 using the 2 reconstructions (see Section 2.1).

3.1 Catch Reconstructions

Estimated catches are summarized in Table 2 (Appendix I) and the catch times series are shown in Figure 1. The catch trend in R1 shows a slow increase into the 1980s, before a period of rapid growth until a peak of 78,081 tonnes is reached in 2017, after which catches begin to decrease. The trend of catches in R2 resembles more closely that of the reported silky shark catch, slowly increasing prior to the 1990's then increasing rapidly from 1991 before reaching a maximum catch of 56,205 tonnes in 1999. This is followed by a rapid decrease then fluctuation around 40,000-50,000 tonnes between around 2005-2019.

3.2 Stock Status

All statistical outputs of the CMSY model for each reconstruction and resilience category used, are summarized in Tables 3 and 4. CMSY outputs for each reconstruction and resilience category are shown in Figure 2. All diagnostic plots produced by CMSY for each scenario are shown in Figure 3 and 4 (Appendix I).

r: Inter-group (r = very low or low) variation in median r output was larger than the comparatively stable intra-group variation, where r= low produced a point estimate of 0.288-0.307 while r= very low produced estimated r values of 0.0485-0.0492.

k, MSY, B_{MSY}: High inter and intra-group variation occurs between these variables, with R2 producing consistently lower values across both ranges of r. .

F_{MSY}, B/k, B/B_{MSY}, F *(all values are for final year)*: All parameters are relatively consistent across both catch reconstructions within the same r categories but differ when comparing results between them. When r= very low, F related statistics were lower, this can be highlighted by the 142% increase seen in the value of Fmsy for r = low relative to r = very low (R1).

F/F_{MSY} (in final year)**:** Median estimates of exploitation rate were somewhat comparable between r categories, however r= low had wider confidence intervals in comparison to r= very low. In both r ranges, F/F_{MSY} of R2 suggests the stock has a lower exploitation rate, in contrast to R1.

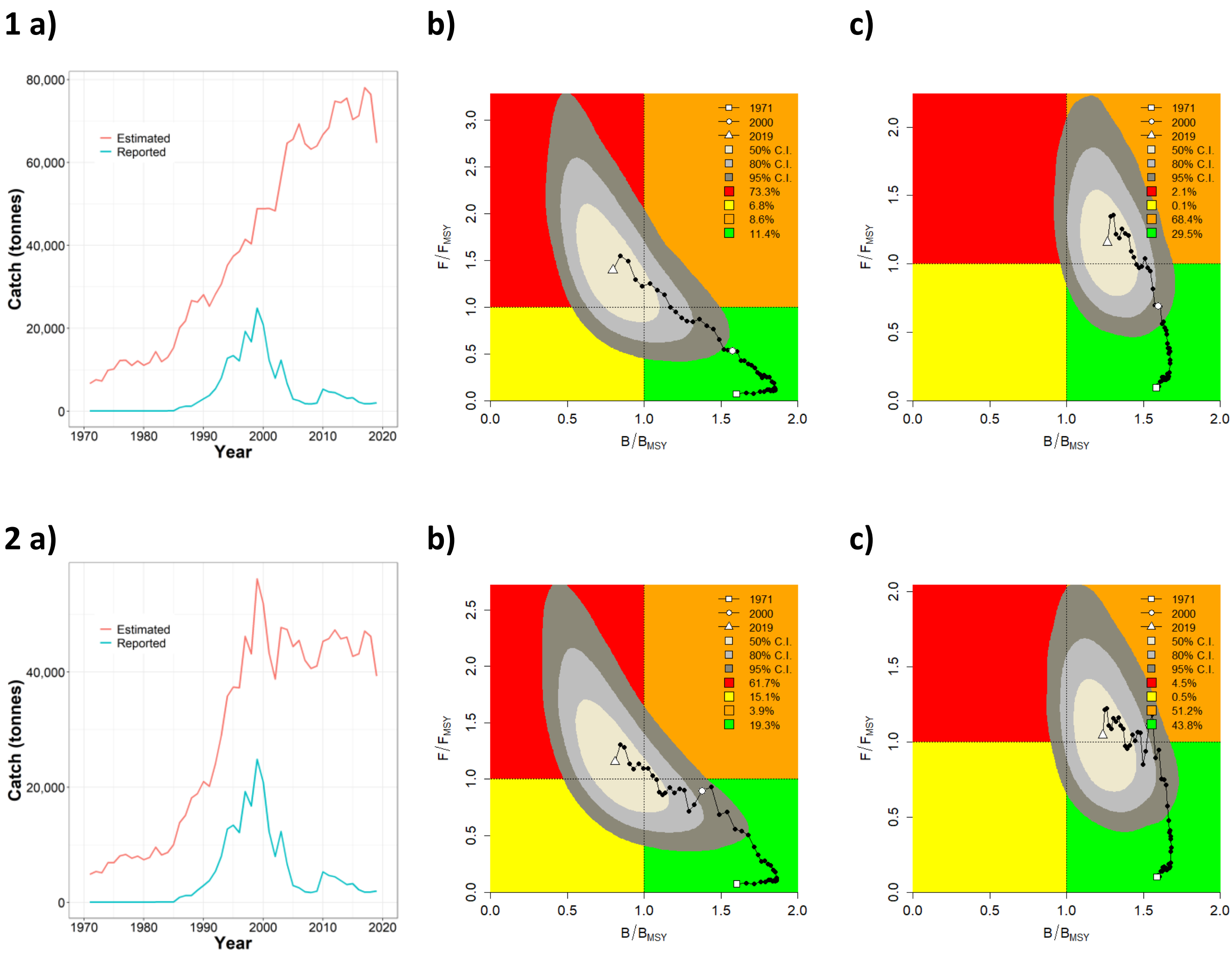

Figure 2. a) Reconstructed catch time series where the orange indicates estimated catch and blue indicates total reported silky shark catch; b) KOBE plots using r = low; c) KOBE plots using r = very low. The KOBE plots for each catch series reconstruction are displaying the change in biomass (B) and fishing mortality (F) relative to MSY (B_{MSY} and F_{MSY}) over time. The vertical line indicates B_{MSY} and the horizontal line indicates F_{MSY}. Grey areas represent confidence intervals (light grey = 50%, grey = 80%, and dark grey = 95%).

Predictions of stock status (2019) between the reconstructions showed R2 is visually comparable to R1 in both r ranges (Figure 2). However, R2 (Figure 2.1) shows a higher probability of good stock status (B/Bmsy > 1 & F/Fmsy < 1) under both r scenarios. Nonetheless, all four assessment models indicate that overfishing is occurring (F/Fmsy > 1). Overall, a more substantial difference in the predicted values of B/Bmsy is seen between the two r ranges relative to the comparatively stable levels of F/Fmsy (Fig.2). With r = very low predicting higher levels of B/Bmsy compared to r = low. This occurs to the extent that when r = very low the median values indicate a stock that is not overfished (B/Bmsy > 1), in contrast to when r = low where median values indicate an overfished stock (B/Bmsy < 1).

As indicated by Figure 2, the degree of uncertainty in the stock status is greater when using r= low, with these results indicating a greater potential for the stock status to be overfished than when r= very low is used.

Table 3. Summary of statistical outputs of CMSY model using r= low for 2 different reconstructions of estimated catch time series. Last year= 2019.

Reference Point	**Reconstruction 1**		**Reconstruction 2**	
	Value	**95% CI**	**Value**	**95% CI**
r	0.288	0.135-0.614	0.307	0.156-0.603
k (1000 t)	810	524-1253	549	351-859
MSY (1000 t)	52.5	37.3-94.5	38.2	28.4-62.9
B_{MSY}	405	262-627	275	175-430
F_{MSY}	0.144	0.0675-0.307	0.153	0.078-0.301
B/k in last year	0.398k	0.209-0.68	0.405k	0.209-0.668
B/B_{MSY} in last year	0.796	0.418-1.36	0.81	0.419-1.38
F in last year	0.201	0.118-0.382	0.177	0.104-0.342
F/F_{MSY} in last year	1.4	0.817-2.66	1.15	0.679-2.23

Table 4. Summary of statistical outputs of CMSY model using r= very low for 2 different reconstructions of estimated catch time series Last year= 2019.

Reference Point	Reconstruction 1		Reconstruction 2	
	Value	95% CI	Value	95% CI
r	0.0485	0.0245-0.0962	0.0492	0.0249-0.0972
k (1000 t)	3654	2392-5582	2481	1619-3801
MSY (1000 t)	42.7	25.7-66.4	29.4	17.5-46.4
B_{MSY}	1827	1196-2791	1241	810-1901
F_{MSY}	0.0243	0.0122-0.0481	0.0246	0.0125-0.0486
B/k in last year	0.634k	0.451-0.697	0.617k	0.418-0.697
B/B_{MSY} in last year	1.27	0.901-1.39	1.23	0.836-1.39
F in last year	0.028	0.0254-0.0393	0.0257	0.0227-0.0379
F/F_{MSY} in last year	1.15	1.05-1.62	1.04	0.924-1.54

4. Discussion

4.1 Stock Status

The variation in results from the stock assessments using different catch reconstructions and r categories indicate the stock status of silky sharks in the Indian Ocean remains uncertain. Stock status results using R2 indicate a lower risk of the stock being overfished compared to R1, potentially a product of the catch trend leveling out from 2003 onwards. However, results from all 4 assessments indicate that fishing mortality is above F_{MSY} and that overfishing is occurring.

Generally, the various catch reconstructions did not have a marked effect on the outcome of the model. The magnitude of the catch reconstructions, however, does influence biomass parameters k, MSY and B_{MSY} since these are directly related to the quantity of catches. The r category used as input for the CMSY model, however, largely influenced the result of the stock assessment where r= low had larger uncertainty in the estimated current stock status and indicated a higher chance of the stock being overfished (B/B_{MSY}), while r= very low indicated a smaller likelihood of the stock being overfished. Despite high variation in values either between or within reconstructions/r categories, F/F_{MSY} remained relatively consistent throughout. Whilst r = low had a larger uncertainty range, work done in WKLIFE V (ICES, 2015) indicated that CMSY method was poorly suited to species with very low resilience. As such, whilst the reliability of the r = very low is higher, further work is needed to prove its validity.

Overall, all stock assessment results show that overfishing is currently occurring and that within the category of r= low, the stock is being overfished while within the category of r= very low, the stock is not yet overfished.

4.2 Catch Reconstructions

Sri Lanka has been the highest reporter of silky shark catches in the Indian Ocean and while the reported catch time series as well as new estimations presented here take this into consideration, it is important to note that estimations here are only based on what is reported. There is potential that other fleets have caught high numbers of silky sharks and not reported to the IOTC.

As estimated catch time series continue to be developed and increase in accuracy, we suggest several factors that could be considered. The first is that reconstructions investigated in this study do not address that many shark species are reported simply as 'sharks nei' and are not species specific (IOTC, 2021). Nor do they consider discards (and associated post-release mortality rates) or issues surrounding ghost-fishing, or any illegal, unreported, or unregulated (IUU) fishing of these species. Therefore, there is potential that silky shark catches are even higher than those estimated here and is something to be investigated. Additionally, susceptibility values of sharks to particular gear types, reported by the 2018 ERA (Murua *et al*.), present potential values to be used as proportions of silky sharks caught to all sharks.

4.3 r value

It is apparent that the prior range of r has a marked influence on the stock status. The preliminary silky shark stock assessment (Ortiz de Urbina *et al.,* 2018) used the r category of very low and reported an estimated r value for silky sharks of 0.062. Fishbase (Froese & Pauly, 2015) also reports an r value of

0.06. Estimated r values produced in this study ranged from 0.262-0.294 using r= low and 0.0454-0.0491 using r= very low. A stock assessment of silky sharks in the Pacific in 2013 (Rice & Harley) found silky sharks to have an r value of 0.102. Additionally, an ERA carried out for shark species in the Atlantic in 2015 (Cortés *et al.*) reported silky sharks as having an r value< 0.5, 0.078 in the North Atlantic, and 0.042 in the South Atlantic. Based on the work of Clarke *et al.* (2015), the Indian Ocean population is closer genetically to the Pacific than the Atlantic population, suggesting the reported r = very low values in this study may be an underestimate or the work of Rice & Harley (2013) is an overestimate.

5. Conclusion

The results from this study indicate that the current stock status of silky sharks in the Indian Ocean is uncertain and is either in the state of being overfished, or overfishing is occurring. While obtaining the most accurate catch time series possible is highly valuable, this study has found that the category of r required as input into the CMSY model has a larger influence on the biomass of the stock and whether it is being overfished or not. Further research into the biological parameters and productivity of silky sharks specifically in the Indian Ocean will aid in better understanding of the intrinsic value of population growth rate (r), seen to be the biggest determinant of stock status. Half of the results generated in this study indicate the stock is being overfished but all indicate that overfishing is currently occurring and therefore it is advisable to adopt the precautionary approach and identify suitable management measures to prevent potential overexploitation of this species, including considering all results presented here as guidance for total allowable catches.

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Appendix I

Table 2. Summary of estimated catches (in tonnes) from years 1971-2019 for reconstructions 1 and 2.

Year	Reconstruction 1	Reconstruction 2
1971	6688	4902
1972	7596	5385
1973	7263	5140
1974	9895	6896
1975	10185	6905
1976	12224	8091
1977	12300	8363
1978	11037	7676
1979	12127	8056
1980	11074	7418
1981	11786	7822
1982	14360	9599
1983	11962	8238
1984	13016	8670
1985	15277	10018
1986	20124	13852
1987	21798	15131
1988	26686	18157
1989	26336	18905
1990	28129	21006
1991	25303	20166
1992	28236	24112
1993	30672	29010
1994	35227	35819
1995	37420	37405
1996	38548	37273
1997	41478	46208
1998	40373	43172
1999	48907	56205
2000	48872	51922
2001	48927	43294
2002	48365	38784
2003	56445	47757
2004	64702	47406
2005	65586	44419
2006	69297	45514
2007	64533	42039
2008	63250	40624
2009	64014	41061
2020	66773	45356
2011	68402	45822
2012	74830	47330
2013	74466	45792
2014	75559	46075
2015	70369	42737
2016	71281	43162
2017	78081	47125
2018	76460	46215
2019	64726	39321

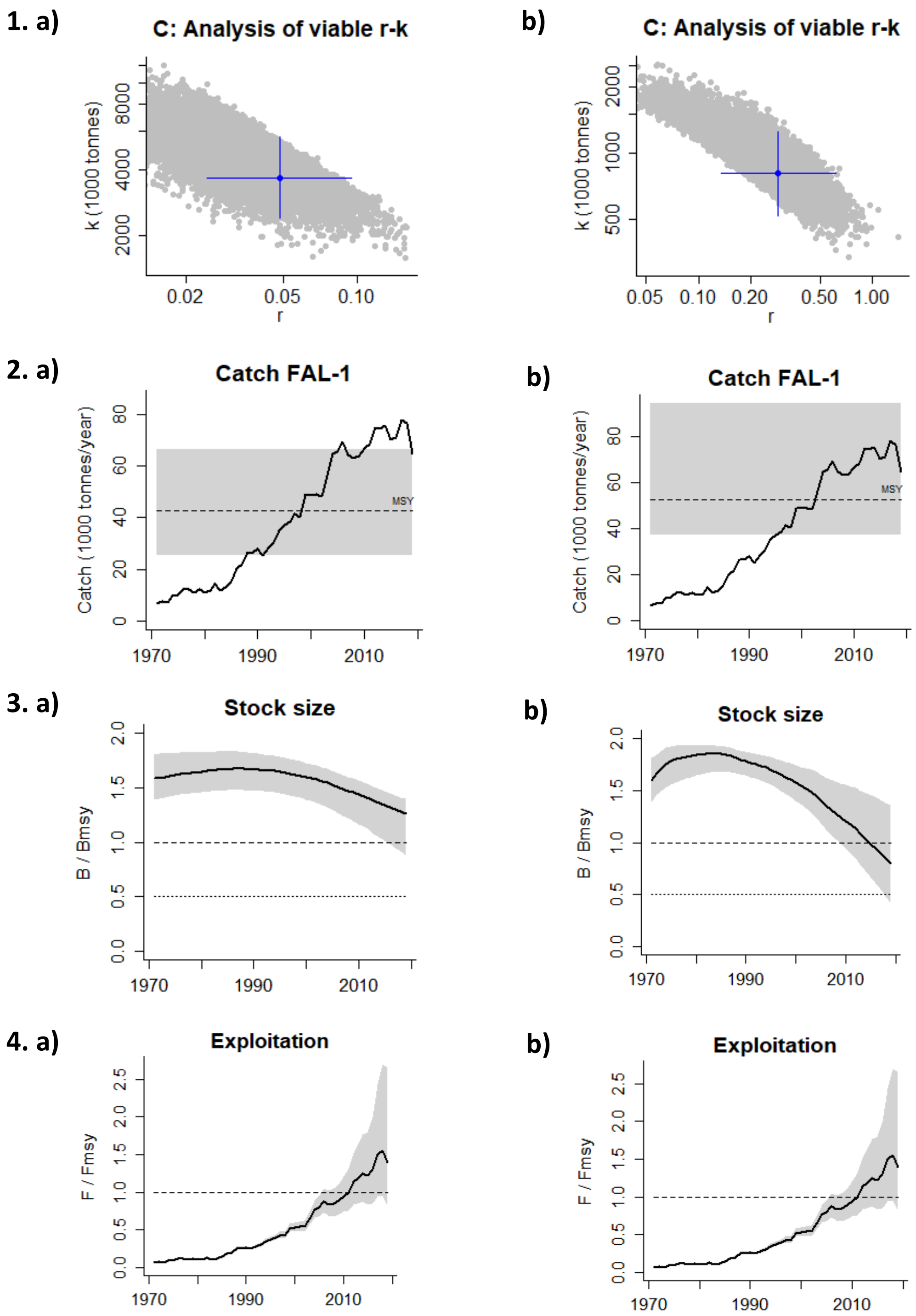

Figure 3. Diagnostic plots generated from CMSY for catch reconstruction 1. Figures on the left (a) show results using r= very low and figures on the right (b) show results using r= low. 1. Viable r-k pairs (grey dots) and best estimates with associated uncertainty (blue crosses). 2. Reconstructed catch time series (solid line) with estimated MSY value (dotted line) and associated confidence intervals (grey area). 3. Estimated stock biomass over time (solid line) with associated confidence intervals (grey area). Estimated B_{MSY} value (horizontal dotted line) and half of B_{MSY} (horizontal solid line). 4. Exploitation rate over time (solid line) with associated confidence intervals (grey area) and estimated F_{MSY} value (dotted line).

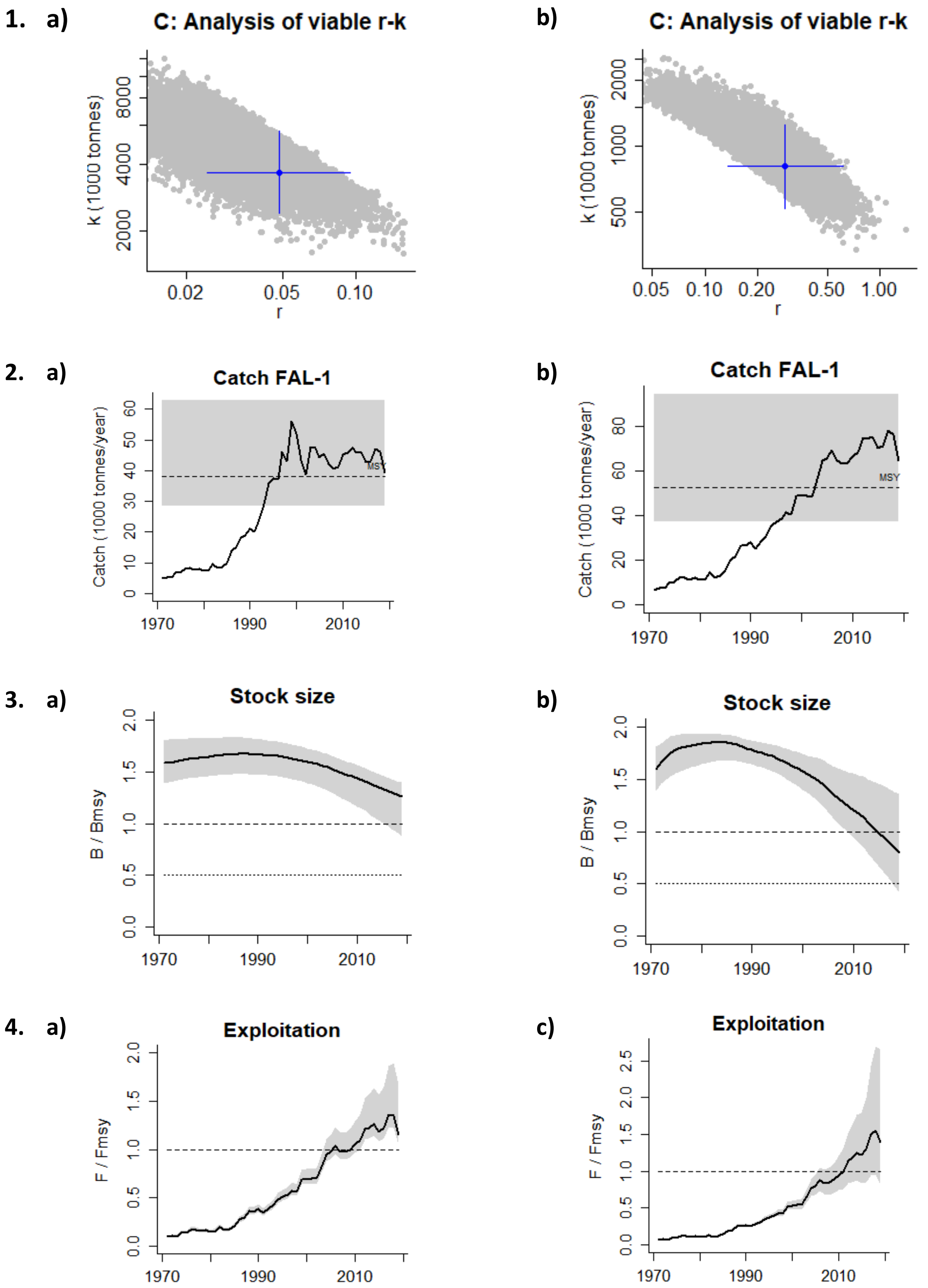

Figure 4. Diagnostic plots generated from CMSY for catch reconstruction 2. Figures on the left (a) show results using r= very low and figures on the right (b) show results using r= low. 1. Viable r-k pairs (grey dots) and best estimates with associated uncertainty (blue crosses). 2. Reconstructed catch time series (solid line) with estimated MSY value (dotted line) and associated confidence intervals (grey area). 3. Estimated stock biomass over time (solid line) with associated confidence intervals (grey area). Estimated B_{MSY} value (horizontal dotted line) and half of B_{MSY} (horizontal solid line). 4. Exploitation rate over time (solid line) with associated confidence intervals (grey area) and estimated F_{MSY} value (dotted line).