Assessment of Indian Ocean Indo-Pacific Sailfish (*Istiophorus platypterus*) using catch-only methods

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1. Introduction

Assessing the status of the stocks of billfish species in the Indian Ocean is challenging due to the paucity of data. There is lack of reliable information on stock structure, abundance and biological parameters. Data poor stock assessments were conducted for Indo-Pacific Sailfish (*Istiophorus platypterus*) in 2015 (Sharma 2015). This paper provides an update to that assessments based on the most recent catch information reported to the IOTC, using a revised Catch-MSY method (Froese et al. 2016). An additional method, stochastic stock reduction analysis, was also used to explore the potential to include the length frequency data in the assessment.

2. Basic Biology

Indo-Pacific (*Istiophorus platypterus*) is an oceanic and epipelagic species usually found above the thermocline, distributed in waters close to coasts and islands (Frimodt1995, Nakamura 1985). The distribution is primarily in the tropical waters of the Indian and Pacific oceans and the species is differentiated from the Atlantic sailfish populations (Froese and Pauly 2015). The stock structure of Indo-Pacific sailfish in the Indian Oceans is uncertain: apparently there are local reproductively isolated stocks. At least one stock was reported in the Persian Gulf with no or very little intermixing with open Indian Ocean stocks. However outside of the Gulf no stock differentiation has been determined. Thus for the purposes of assessment, one pan-ocean stock is assumed. However, spatial heterogeneity in stock indicators (catch–per–unit–effort trends) for other billfish species indicates that there is potential for localised depletion.

The Indo-Pacific sailfish feeds mainly on fishes, crustaceans and cephalopods. It is one of the smallest-sized billfish species but is relatively fast growing. Individuals may grow to over 3 m and up to 100kg with a maximum age of 13 years. Spawning in Indian waters occurs between December to June with a peak in February and June. In subtropical waters of the southern hemisphere spawning is associated with warmer months: in Mozambique Channel and around Reunion Island high percentage of ripe females occurs in December.

3. Fisheries and catch trends

Nominal catch data were extracted from the IOTC Secretariat database for the period 1950 – 2017, given that records for 2018 were still incomplete (Table 1). Gillnets account for around 70% of total catches in the Indian Ocean, followed by troll and hand lines (21%), with remaining catches recorded under longlines and other gear. Most catches were taken by coastal country fleets, namely I.R. Iran, India, Pakistan, and Sri Lanka (Figure 1). Catches have increased sharply since the mid-1990's (from around 5,000 t in the early 1990s to nearly 30,000 t from 2011 onwards) largely due to the development of a gillnet/longline fishery in Sri Lanka and, especially, the extension of Iranian gillnet vessels operating in areas beyond the EEZ of I.R. Iran (Figure 2).

There is a relatively large uncertainty associated with the catch data for Indo-Pacific sailfish as a very high proportion of the catches of Indo-Pacific sailfish are estimated, or adjusted, by the IOTC Secretariat due to several uncertainties related to the reporting of catches (IOTC 2018). Therefore, the IOTC Secretariat uses various methods of estimating the disaggregated catches by species for assessment purposes. However, unlike the other billfish species, Indo-Pacific sailfish are more reliably identified.

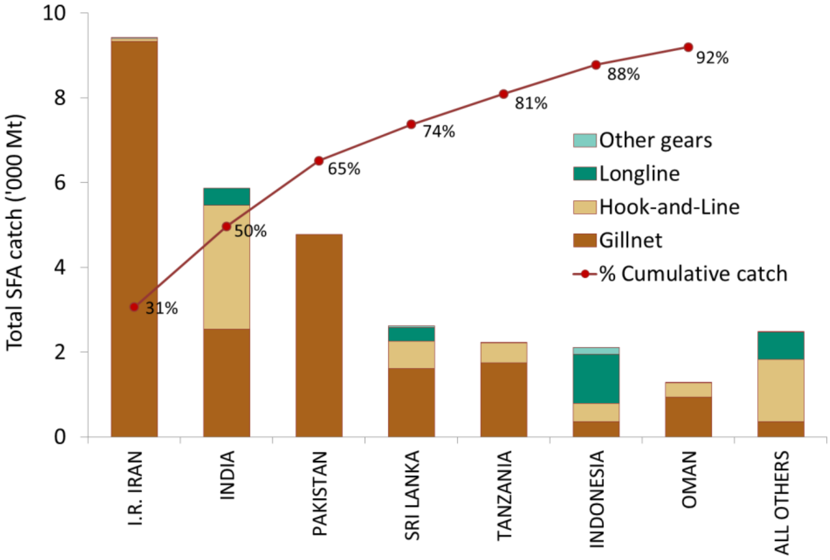

Figure 1. Average catches in the Indian Ocean over the period 2013-2017, by country. The red line indicates the (cumulative) proportion of catches of Indo-Pacific sailfish by country.

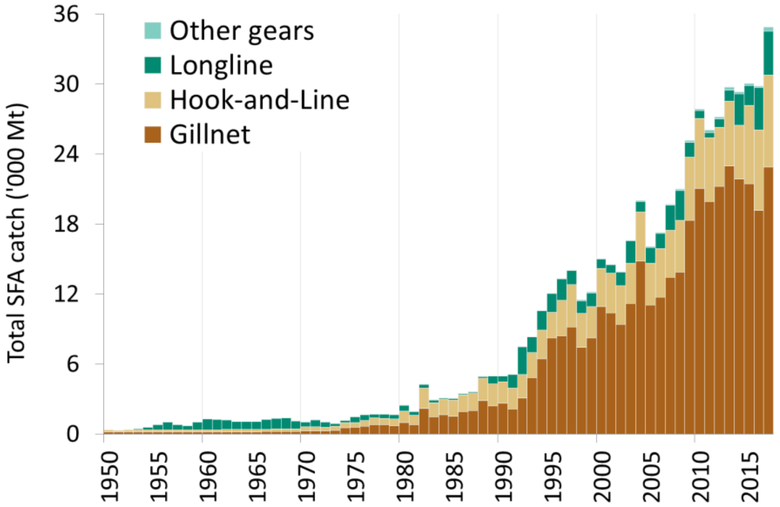

Figure 2. Annual catches of Indo-Pacific sailfish by gear, 1950 – 2015 (IOTC database)

Table 1. Catch data for *T. tonggol* in the Indian Ocean, 1950-2015 (source IOTC Database)

Year	Catch (t)	Year	Catch (t)
1950	336	1984	3,124
1951	317	1985	3,061
1952	359	1986	3,479
1953	428	1987	3,655
1954	577	1988	4,930
1955	804	1989	4,985
1956	1,009	1990	4,974
1957	787	1991	5,119
1958	697	1992	7,480
1959	1,014	1993	8,365
1960	1,305	1994	10,622
1961	1,257	1995	12,070
1962	1,180	1996	13,353
1963	1,054	1997	14,042
1964	1,047	1998	11,479
1965	1,048	1999	12,155
1966	1,226	2000	15,055
1967	1,346	2001	14,544
1968	1,389	2002	13,929
1969	1,119	2003	16,626
1970	1,026	2004	20,001
1971	1,206	2005	16,051
1972	1,003	2006	17,291
1973	860	2007	19,719
1974	1,166	2008	20,986
1975	1,470	2009	25,143
1976	1,656	2010	27,797
1977	1,700	2011	25,915
1978	1,706	2012	27,385
1979	1,673	2013	30,026
1980	2,475	2014	28,279
1981	1,917	2015	29,556
1982	4,249	2016	28,218
1983	2,932	2017	33,320

4. Methods

4.1. C-MSY method

We applied the C-MSY method of Froese et al. (2016) to estimate reference points from catch, resilience and qualitative stock status information for Indo-Pacific sailfish. The C-MSY method represents a further development of the Catch-MSY method of Martell and Froese (2012), with a number of improvements to reduce potential bias. Like the Catch-MSY method, The C-MSY relies on only a catch time series dataset, which was available from 1950 – 2017, prior ranges of *r* and *K*, and possible ranges of stock sizes in the first and final years of the time series.

The Graham-Shaefer surplus production model (Shaefer 1954) is used (equation 1), but it is combined with a simple recruitment model to account for the reduced recruitment at severely depleted stock sizes (equation 2), where B_t is the biomass in time step t, r is the population growth rate, B_0 is the virgin biomass equal to carrying capacity, K, and C_t is the known catch at time t. Annual biomass quantities can then be calculated for every year based on a given set of r and K parameters.

$$B_{t+1} = \left[B + r\left(1 - \frac{B_t}{K}\right)B_t - C_t \right] \qquad \text{if } \frac{B_t}{K} > 0.25 \qquad (1)$$

$$B_{t+1} = \left[B + 4\frac{B_t}{K}r\left(1 - \frac{B_t}{K}\right)B_t - C_t \right] \qquad \text{if } \frac{B_t}{K} \le 0.25 \qquad (2)$$

There are no known prior distributions of the parameters r and K, so a uniform distribution was used from which values were randomly drawn. A reasonably wide prior range was set for r based on the known level of resilience of the stock as proposed by Martell and Froese (2012) where stocks with a very low resiliency are allocated an r value from 0.05 – 0.5, medium resiliency 0.2 – 1 and high resiliency 0.6 – 1.5. Based on the FishBase classification, *I. platypterus* has a low level of resilience and a range of 0.16 – 0.49 was used (Froese and Pauly 2015). The prior range of K was determined as

$$k_{low} = \frac{\max(C_t)}{r_{high}}, k_{high} = \frac{4\max(C_t)}{r_{low}} \qquad (3)$$

Where k_{low} and k_{high} are the lower and upper lower bound of the range of k, max(C) is the maximum catch in the time series, and r_{low} and r_{high} are lower and upper bound of the range of r values.

The ranges for starting and final depletion levels were assumed to be based on one of possible three biomass ranges: 0.01–0.4 (low), 0.2–0.6 (medium), and high (0.5–0.9), using a set of rules based on the trend of the catch series (see Froese et al. (2016) for details). With this approach, the prior range for the depletion level can also be assumed optionally for an intermediate year, but we did not explore this option in this report. This resulted in the prior ranges used for key parameters as specified in C-MSY estimates biomass, exploitation rate, MSY and related fisheries reference points from catch data and resilience of the species. Probable ranges for r and k are filtered with a Monte Carlo approach to detect 'viable' r-k pairs. The model worked sequentially through the range of initial biomass depletion level and random pairs of r and K were drawn based on the uniform distribution for the specified ranges. Equation 1 or 2 is used to calculate the predicted biomass in subsequent years, each r-k pair at each given starting biomass level is considered variable if the stock has never collapsed or exceeded carrying capacity and that the final biomass estimate which falls within the assumed depletion range. All r-k combinations for each starting biomass which were considered feasible were retained for further analysis. The search for viable r-k pairs is terminated once more than 1000 pairs are found.

The most probable r-k pair were determined using the method described by Ferose et.al (2016). All viable r-values are assigned to 25–100 bins of equal width in log space. The 75th percentile of the mid-values of occupied bins is taken as the most probable estimate of r. Approximate 95% confidence limits of the most probable r are obtained as 51.25th and 98.75th percentiles of the mid-values of occupied bins, respectively. The most probable value of k is determined from a linear regression fitted to *log(k)* as a function of log(r), for r-k pairs where r is larger than median of mid-values of occupied bins. MSY are obtained as geometric mean of the MSY values calculated for each of the r-k pairs where r is larger than the median. Viable biomass trajectories were restricted to those associated with an r-k pair that fell within the confidence limits of the C-MSY estimates of r and k.

Table 2.

C-MSY estimates biomass, exploitation rate, MSY and related fisheries reference points from catch data and resilience of the species. Probable ranges for r and k are filtered with a Monte Carlo approach to detect 'viable' r-k pairs. The model worked sequentially through the range of initial biomass depletion level and random pairs of *r* and *K* were drawn based on the uniform distribution for the specified ranges. Equation 1 or 2 is used to calculate the predicted biomass in subsequent years, each *r-k* pair at each given starting biomass level is considered variable if the stock has never collapsed or exceeded carrying capacity and that the final biomass estimate which falls within the assumed depletion range. All *r-k* combinations for each starting biomass which were considered feasible were retained for further analysis. The search for viable r-k pairs is terminated once more than 1000 pairs are found.

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Table 2. Prior ranges used for IP sailfish for the C-MSY analysis

Species	**Initial B/K**	**Final B/K**	***r***	***K (1000 t)***
IP sailfish	0.5–0.9	0.3–0.7	0.16–0.5	62 – 759

4.2. Stochastic Stock Reduction Analysis

The C-MSY method used the Schafer surplus-production model which imposes strong assumptions on the productivity of the stock. Although the estimate of MSY is generally robust with both methods, estimates of other management quantities are sensitive to the assumed level of stock depletion. Below we explored the stochastic stock reduction analysis approach (Stochastic SRA) by Walters et al. (2004), as implemented in the Data Limited Methods toolkit (Carruthers et al. 2014), as an attempt to overcome some of these limitations. The Stochastic SRA uses an age-structured model and incorporates time series of age-frequency data to condition feasible biomass trajectories, without making explicit assumptions about the level of stock depletion.

The stochastic SRA uses historical catches to estimate recruitment rates that can support those catches, also consistent with the age frequency data (Walters et al. 2004). It uses Monte Carlo simulations to provide distributions for feasible stock size over time under alternative hypotheses about unfished recruitment rates and about variability around assumed stock–recruitment relationships (Walters et al. 2004). The use of an age structure model utilized the information on life history parameters of the species; the inclusion of the age frequencies accounts for potential recruitment variabilities. Estimation of reference points such as unfished biomass (B0) or target biomass (BMSY) are estimated from the population model.

The model is implemented in the *Stochastic_SRA* function of the R package DLMtools (see Carruthers et.al. 2014 for the full description of the model). The model is age-structured with a maximum age of 13, and includes population processes such as recruitment, aging, natural- and fishing mortality. Most model parameters (e.g. growth, maturity, and natural mortality, etc.) were allowed to vary across simulations, and were sampled from a uniform distribution with the lower and upper bounds detailed in Table 3. The parameter values are based on available information on life history of *I. platypterus* from FishBase and are subject to high certainty. The Beverton-Holt stock recruitment relationship was assumed with a steepness parameter ranging from 0.3 to 0.9. Further stochasticity was introduced by allowing for both annual variability and time-varying trend for several parameters (Table 3). For example, natural mortality was assumed to range from 0.3 to 0.4 (loosely corresponding to a maximum age of 13) and vary between -5% and 5% from year to year with an annual standard deviation ranging 0–0.1. Annual variations were also allowed for catchability (see Table 3). Additional errors were incorporated in the catch series, with an assumed CV 0.2 – 0.6. The population is assumed to reside in two areas: a fished area and an area not subject to fishing. We further assumed that the fraction of the unfished biomass in the protected area ranges from 0.05 to 0.1, and the fish has an annual probability between 0.85 and 0.98 of remaining within the fished area (see Table 3).

The model was run from 1950 to 2017 with parameters sampled from the specified distribution, and only parameters that generate feasible population trajectories were retained. A population trajectory is considered to be feasible if it supports the known historical catches and if the difference between the expected age frequencies and observed age frequencies is below a pre-defined threshold value. The age frequencies are converted from the commercial length frequency samples of IP sailfish (Figure 3 – left). The length data are for all gears combined and are available for 1970-2017. Only the years in which the sample size is greater than 500 were retained for the analysis. The numbers of fish in each age class (1 – 13) was determined by applying an age-length key to the length composition. The age-length key was derived by assuming an equilibrium population age-length structure based on an assumed natural mortality of 0.35, the average length-at-age from the IP sailfish growth parameters and the standard deviation of length-at-age (CV 0.1) (Figure 3 – right). The time series of age frequency is shown in Figure 4. The model estimates an age-based, logistic selectivity ogive when predicting the expected age frequencies from the fisheries.

Table 3: Parameters used for the stochastic stock reduction analysis of IP sailfish. The parameters are sourced from FishBase (Froese and Pauly 2015).

Parameter	Value	Definition
maxage	13	The maximum age of individuals that is simulated
M	0.30 – 0.40	Natural mortality rate
Msd	0–0.1	Inter-annual variability in natural mortality rate expressed as a CV
Mgrad	(-0.05 – 0.05)	Percentage change in M per yeartrend in natural mortality rate, expressed as a percentage change in M per year
h	0.3 – 0.95	Steepness of the stock recruit relationship
SRrel	1	Beverton-Holt SR relationship
Linf	250 – 260	Maximum length

K	0.10 – 0.40	von B. growth parameter k
t0	(-1)	von B. theoretical age at length zero
Ksd	0 – 0.01	Inter-annual variability in growth parameter k
Linfsd	0 – 0.01	Inter-annual variability in maximum length - uniform distribution
a	0.000016	Length-weight parameter alpha
b	2.74	Length-weight parameter beta
D	0.10–0.8	Current level of stock depletion
L50	150–160	Length-at- 50 percent maturity
L50_95	5 – 10	Length increment from 50 percent to 95 percent maturity
Perr	0.15–0.3	Process error, CV of recruitment deviations
AC	0.1 – 0.9	Autocorrelation in recruitment deviations
Frac_area_1	0.05 – 0.10	The fraction of the unfished biomass in stock 1
Prob_staying	0.8 –0.98	The probability of individuals in area 1 remaining

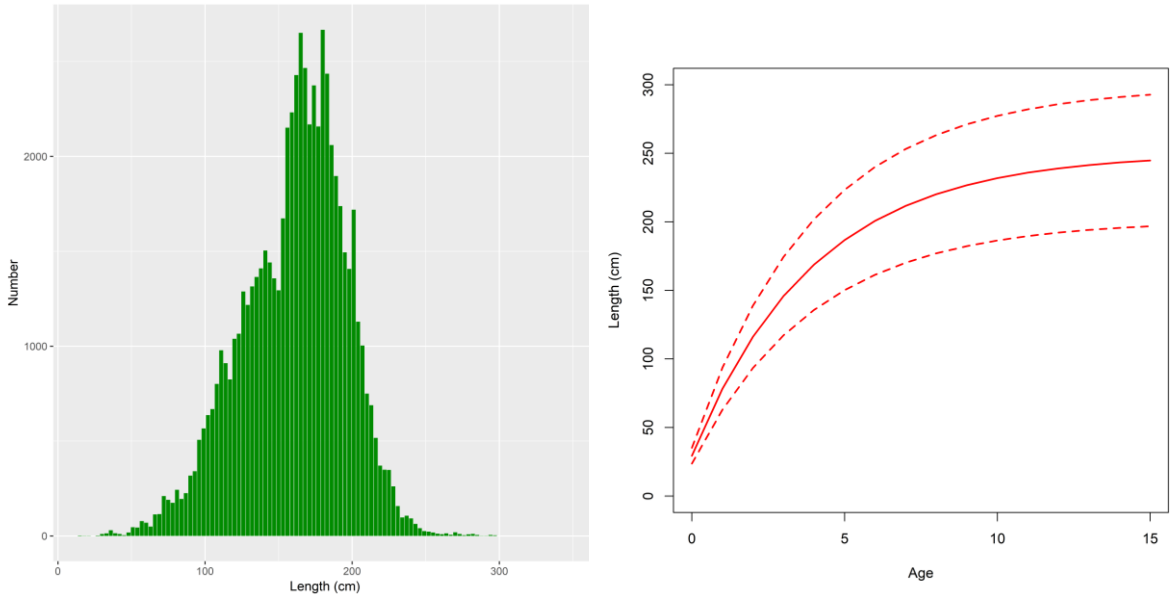

Figure 3: The aggregated length frequency of IP sailfish for all gears and years (1970-2017) combined from IOTC database (Left), and the VonB growth used to derive the age-length key.

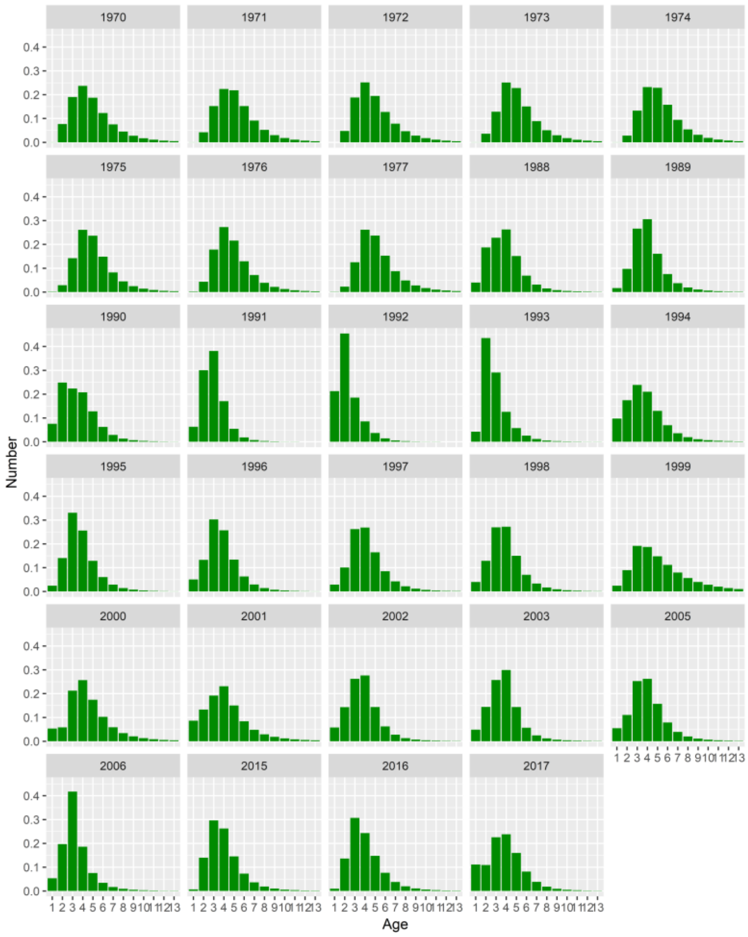

Figure 4: Time series of age frequencies of IP sailfish used in the Stochastic stock reduction analysis. The age frequency was converted from the length frequency data via an age-length-key.

5. Results

5.1. C-MSY method

Figure 5 shows the results of the CMSY assessment for IP sailfish. Panel A shows the time series of catches in black and the three-years moving average in blue with indication of highest and lowest catch, as used in the estimation of prior biomass by the default rules. The use of a moving average is to reduce the influence of extreme catches.

Panel B shows the explored r-k values in log space and the r-k pairs found to be compatible with the catches and the prior information. Panel C shows the most probable r-k pair and its approximate 95% confidence limits. The probable r values did not span through the full prior range, instead ranging from 0.28 – 0.48 (mean of 0.37) while probable K values ranged from 162 000 – 412 000 (mean of 258 000). Given that r and K are confounded, a higher K generally gives a lower r value. CMSY searches for the most probable r in the upper region of the triangle, which serves to reduce the bias caused by the triangular shape of the cloud of viable r-k pairs (Ferose et al. 2016).

Panel D shows the estimated biomass trajectory with 95% confidence intervals (Vertical lines indicate the prior ranges of initial and final biomass). The method is highly robust to the initial level of biomass assumed (mainly due to the very low catches for the early part of series), while the final depletion range has a determinative effect on the final stock status. The biomass trajectory closely mirrors the catch curve with a rapid decline since the early 1990s.

Panel E shows in the corresponding harvest rate from CMSY. Panel F shows the Schaefer equilibrium curve of catch/MSY relative to B/k. However, we caution that the fishery was unlikely to be in an equilibrium state in any given year.

Figure 6 shows the estimated management quantities. The upper left panel shows catches relative to the estimate of MSY (with indication of 95% confidence limits). The upper right panel shows the total biomass relative to Bmsy, and the lower left graph shows exploitation rate F relative to Fmsy. The lower-right panel shows the development of relative stock size (B/Bmsy) over relative exploitation (F/Fmsy).

The IOTC target and limit reference points for IP sailfish have not yet been defined, so the values applicable for other IOTC species are used (i.e. swordfish). Management quantities (estimated means and 95% confidence ranges) are provided in Table 4, which shows an average MSY of about 23 900 t. The KOBE plot indicates that based on the C-MSY model results, IP sailfish is not overfished (B2017/BMSY=1.13) but is subject to overfishing (F2017/FMSY = 1.14). The average catch over the last five years is higher than the estimated MSY.

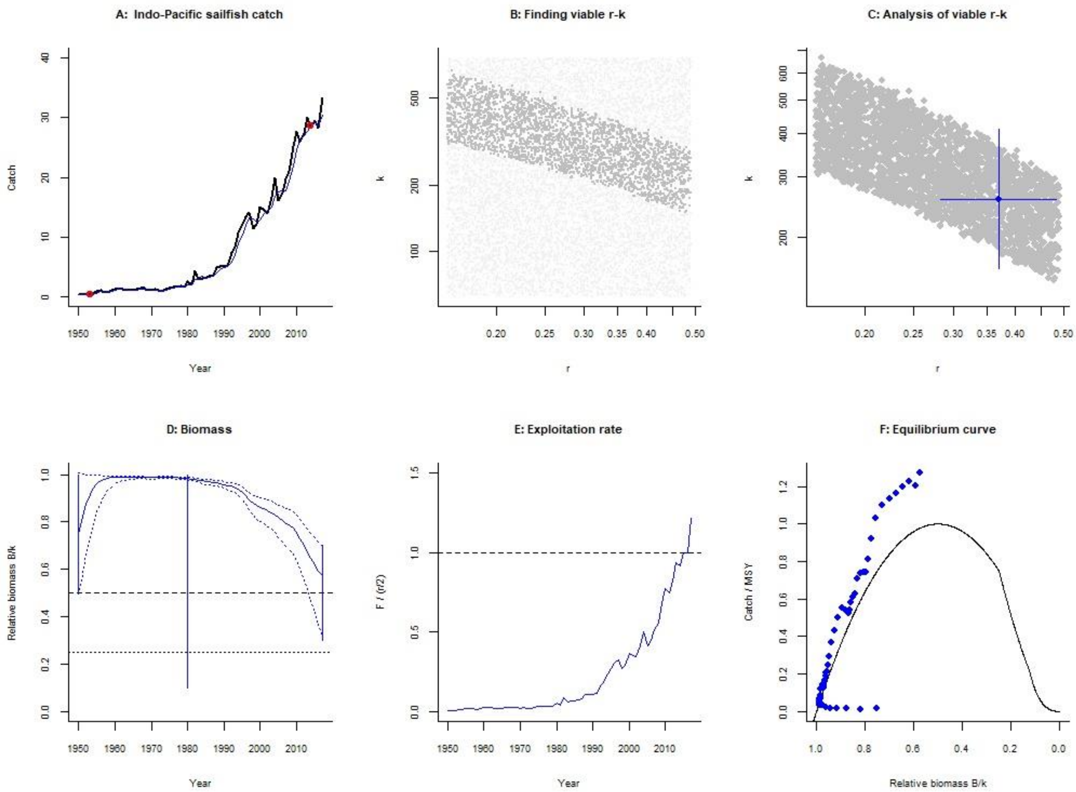

Figure 5. Results of CMSY analyses for IP sailfish.

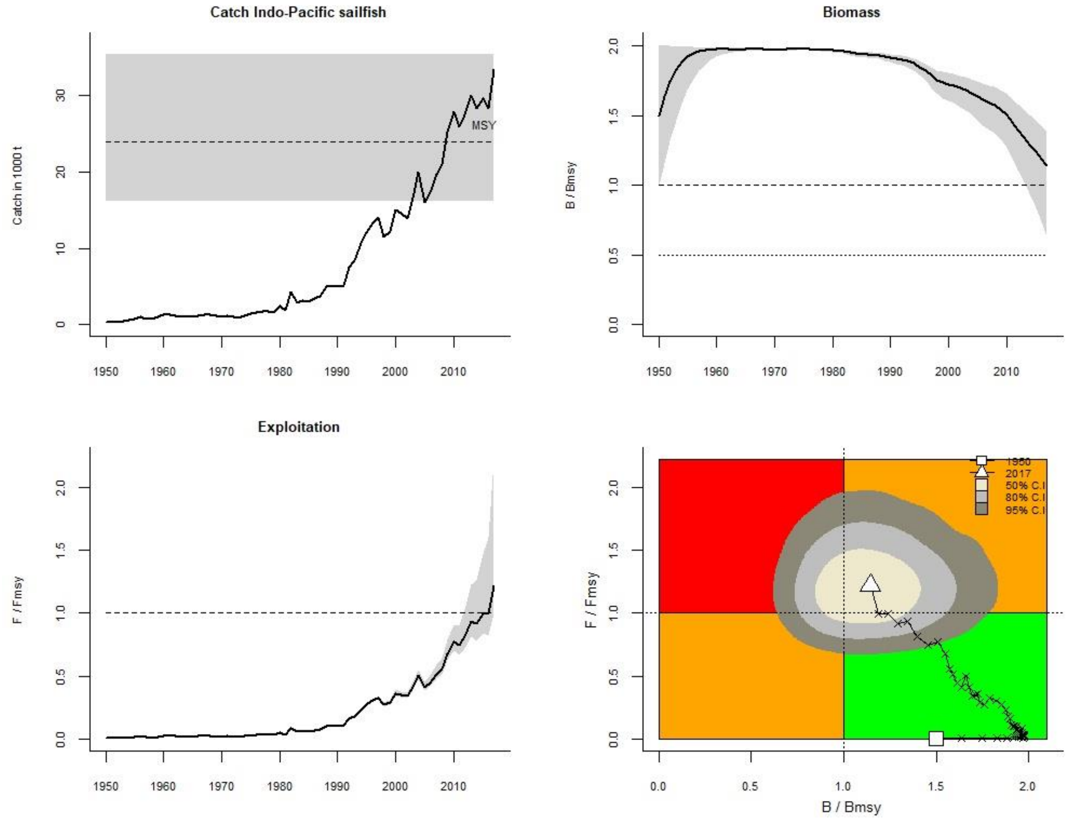

Figure 6. Graphical output of the CMSY analysis of IP sailfish for management purposes.

Table 4. Key management quantities from the Catch MSY assessment for Indian Ocean IP sailfish. Geometric means (and plausible ranges across all feasible model runs). n.a. = not available. Previous assessment results are provided for comparison.

Management Quantity	**2015**	**2019**
Most recent catch estimate (year)	30 674 t (2014)	33 320 t (2017)
Mean catch – most recent 5 years[2]	29 143 t (2010 – 2014)	29 880 t (2013 – 2017)
MSY (95% CI)	25 000 (17 200 – 36 300)	23 900 (16 100 – 35 400)
Data period used in assessment	1950 – 2014	1950 – 2017
F_{MSY} (95% CI)	0.26 (0.15 – 0.39)	0.19 (0.14 - 0.24)
B_{MSY} (95% CI)	87 520 (56 300 – 121 020)	129 000 (81 000 – 206 000)
$F_{current}/F_{MSY}$ (95% CI)	1.05 (0.63 – 1.63)	1.22 (1 – 2.22)
$B_{current}/B_{MSY}$ (95% CI)	1.13 (0.87 – 1.37)	1.14 (0.63 – 1.39)
$B_{current}/B_0$ (95% CI)	0.57 (0.44 – 0.69)	0.57 (0.31 – 0.70)

[2] Data at time of assessment

5.2. Stochastic Stock Reduction Analysis

Results from the Stochastic SRA are shown in Figures Figure 7Figure 8. Three hundred feasible samples were generated from over 2000 simulations. A small number of samples were then excluded as they have resulted in a final stock status less than 10% of the unexploited level, which was assumed to be unlikely. Estimated fishing selectivity reaches the maximum at about age 4. Estimates of recruitment appear very noisy and show a pulse in the early 1990s, corroborating a few strong year classes of two-year old in the observed age frequency. The predicted age distributions are dominated by two to five years old, but older fish are also evident. There is a reasonably good correspondence between observed and predicted age distributions (Figure Figure 7). Estimated spawning stock biomass span a very wide range indicating a high level of uncertainty and the model's inability to constrain some of the large values of biomass (FigureFigure 8). However, estimated stock deletion (SSB/B0) appears consistent amongst simulations with current depletion being about 47% on average. Estimates of fishing mortality are noisy but exhibited a clear increasing trend in line with the catch history (despite that the large uncertainty of the catches has been explicitly incorporated in the simulations).

Estimates of management quantities are shown in Table 5. MSY is estimated to range from 14 310 to 65 040 t with an average 33 310 t. The catch in 2017 is about 4% higher than the mean MSY but is well within the estimated range. The large values of MSY are apparently associated with the large biomass produced in some simulations. Spawning stock biomass in 2017 is estimated to be 52% higher than BMSY and the current fishing mortality is about 25% higher than the FMSY. These estimates suggest that the stock is not overfished but overfishing has occurred (the same conclusion as the C-MSY model). Estimated stock status is associated with very large uncertainty, as evident in their wide confidence bound (Figure 9).

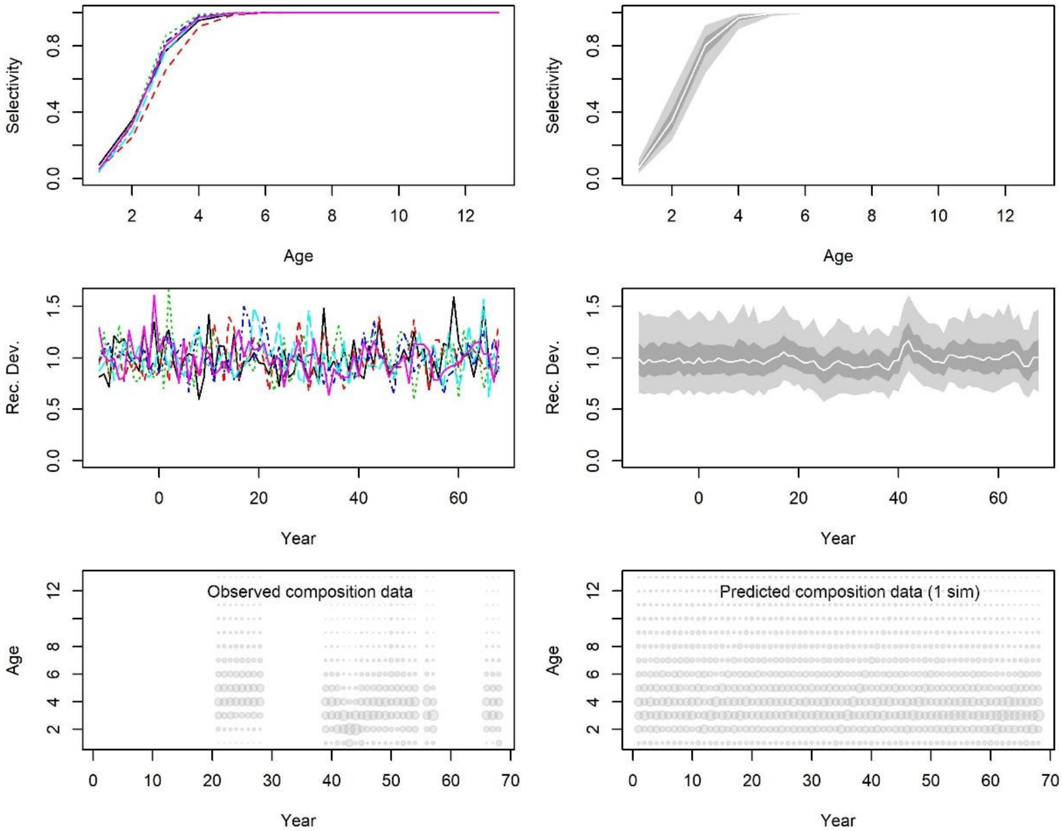

Figure 7: Estimates of age-based selectivity (1st row) and annual recruitment deviation (2nd row) from Stochastic SRA. The left panel shows realisations from 3 samples, and the right panel shows the median and 90% quantile. The third row shows the observed (left) and predicted (right) age frequencies. Year 1 to 60 represents 1950 to 2017.

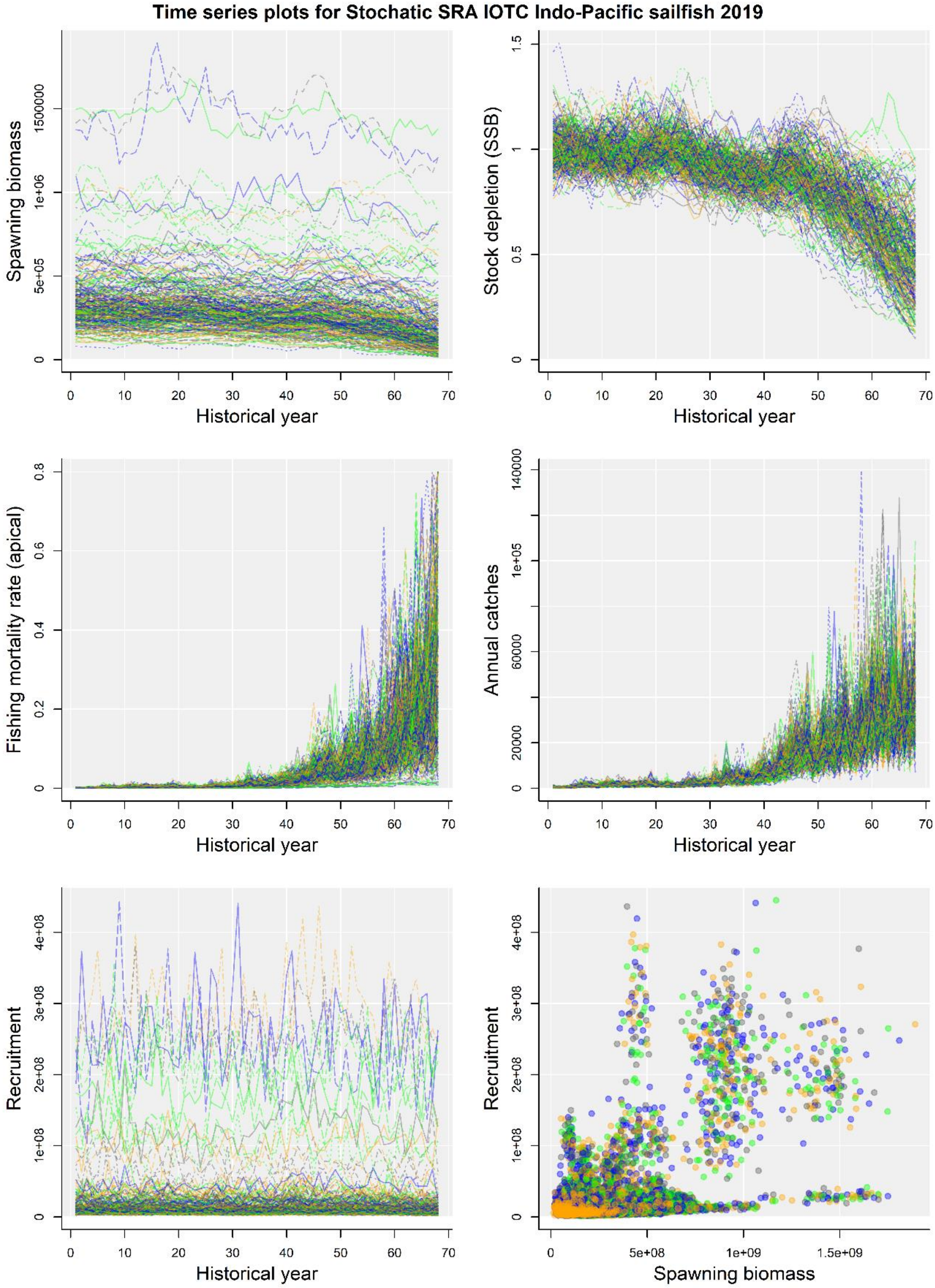

Figure 8: Predictions from the Stochastic SRA including feasible spawning biomass trajectories, depletion, fishing mortality, and annual recruitment estimates.

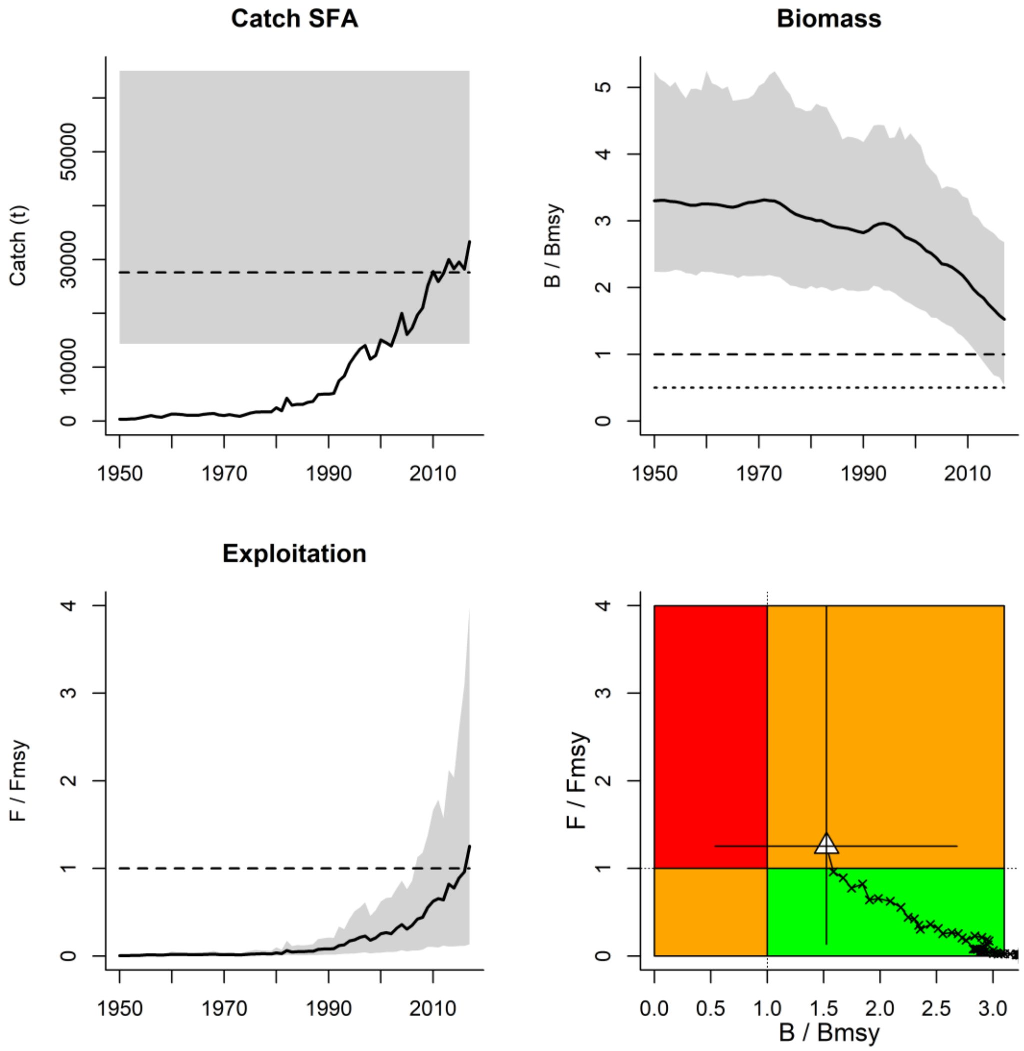

Figure 9: Management quantities of stochastic SRA.

Table 5: Management quantities from the Stochastic SRA for Indian Ocean IP sailfish tuna, means and 95% confidence interval.

Management Quantity	**2019**
MSY (95% CI)	33 310 t (14 310 – 65 040)
Data period used in assessment	1950 – 2017
F_{MSY} (95% CI)	0.36 (0.08 – 0.90)
B_{MSY} (95% CI)	114 415 t (39 550– 248 618)
$F_{current}/F_{MSY}$ (95% CI)	1.25 (0.14 – 4.00)
$SB_{current}/SB_{MSY}$ (95% CI)	1.52 (0.54 – 2.68)
$SB_{current}/SB_0$ (95% CI)	0.46 (0.16 – 0.82)

6. Discussion

In this report we have explored two data-limited methods in assessing the status of Indian Ocean IP sailfish: C-MSY and stochastic SRA. The C-MSY method is based on the aggregated biomass dynamic model and provides an update of the previous assessment using a revised catch-only method. The stochastic SRA uses an age-structured model and has incorporated additional time series of age frequency data. Both models have essentially employed the stock reduction analysis framework, i.e. the use of simulations to locate feasible historical biomass that support the known catch history of the concerned species. Despite the differences in population dynamics and model assumptions, the two models have yielded broadly similar results, and estimates from both models suggest the currently the stock of IP sailfish in the Indian Ocean is not overfished (B2017 > BMSY) but is likely to subject to overfishing (F2017 > FMSY). The estimates produced by the C-MSY method are also similar to the previous assessment (see **Table 4**).

The estimate of MSY differed somewhat between the two models. The C-MSY estimated a mean MSY of approx. 23 900 t with a relatively narrow range. The Stochastic SRA estimated a mean MSY of approx. 33 310 t with a much wider confidence bound. Reported catches of IP sailfish in the Indian Ocean remain relatively stable from 2013 to 2017 and ranged between 28 220 and 33 310 t. The recent catches are above the C-MSY estimates of MSY, but below the estimate from the stochastic SRA model. However, both models have produced a F/FMSY ratio above 1.00 for 2017 and this ratio has been increasing over the last few years. Despite the substantial uncertainties described throughout this paper, this suggests that the stock is very close to being fished at MSY levels and that higher catches may not be sustained. A precautionary approach to management is recommended.

The C-MSY assessment is based primarily on the catch data and an underlying Schaefer model. Production models often provide robust or stable estimates regardless of uncertainties in basic biological characteristics (IOTC 2019). In general, simple model cannot represent important dynamics and thus is more likely to yield biased results. The consistent estimates amongst C-MSY simulations are largely attributed to the strong assumptions imposed on the population dynamics and stock productivity, including the intrinsic growth rate and carrying capacity parameters. The assumption made on the terminal depletion level is subjective but is highly influential to estimates of stock status.

On the other hand, highly parameterised, structured models can describe detailed population and fishing processes, but the estimates are often subject to higher level of uncertainty as structured models often require the support of a diverse range of data. The Stochastic SRA used a more realistic age structured population dynamics, and utilised available life-history parameters of the species and fishery data beyond catch series. It was intended to provide an improvement over the catch-only method. However, estimates of key quantities (e.g. B0 and MSY) using this approach are highly uncertain. The model relies on information of key biological parameters such as growth and natural mortality, most of which are sourced from independent studies and are highly variable. The model did not make explicit assumptions on the depletion levels of the stock yet there is little information available that provides the model with a realistic upper bound on the biomass or recruitment. Observations of age distributions appear stable overtime and are not very informative in terms of estimating the level of fishing pressure. Further it is currently unknown whether the age/length data are representative of the age/size structure of the population. The length data in the IOTC database for IP sailfish are known to be highly incomplete: the data were available only for selected fisheries, total numbers of samples vary across all years, are also well below the minimum sampling standard recommended by the IOTC Secretariat.

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