Assessment of Indian Ocean Bullet tuna (*Auxis rochei*) using data-limited methods

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1. Introduction

Assessing the status of the stocks of neritic tuna 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. There has been no formal stock assessment conducted for bullet tuna (*Auxis rochei*). Fu (2021) provides a preliminary assessment of *A.rochei* using data-limited methods. This paper provides an update of that assessment using the C-MSY method (Froese et al. 2016), based on the most recent catch information, and a length-based method for estimation of spawning potential ratio (Hordyk et al. 2014), based on the available length composition data from the gillnet fishery.

2. Basic Biology

Bullet tuna (Auxis thazard) is a highly migratory pelagic species occurring in neritic zones of the Atlantic (including the Mediterranean Sea), Indian and (western) Pacific oceans. Bullet tuna is an abundant and small schooling species that constitutes an important element of pelagic food webs as prey for larger tuna species and billfishes (Froese & Pauly 2016).

3. Catch, CPUE and Fishery trends

Nominal catch data were extracted from the IOTC Secretariat database for the period 1950–2022, given that records for 2023 were still incomplete at the time of writing. Nominal catches of *A. rochei* are lower than many of the other neritic species, with a total catch of only 23,210 t reported in 2022 (Table 1). Bullet tuna was traditionally caught by gillnets and lines, with smaller amounts taken as bycatch in purse seine fisheries. However, catches by purse seiners increased markedly since 2015, and now exceed those taken by gillnets and lines. The vast majority (>90%) of catches in recent years are accounted for by fisheries in Sri Lanka, Indonesia, and India. (Figure 1 and Figure 2).

In 2019, IOTC endorsed the revisions of Pakistani gillnet catches that introduce some changes in the catches of tropical tuna, billfish, as well as some neritic tuna species since 1987 (IOTC–WPDCS15 2019). However, the revision appears to have very minor effects on the bullet tuna nominal catch series (Figure 3). Alternative estimates of nominal catches are also available (up to 2019) from the catch reconstruction work of the "Sea around us" project (Heidrich et al. 2023).

There is a relatively high uncertainty associated with the catch data for neritic tunas due to the difficulties in differentiating amongst the different species resulting in highly aggregated reported data, often as 'seerfishes' or other groupings. Therefore, the IOTC Secretariat uses various methods of estimating the disaggregated catches by species for assessment purposes. Fu & Martin (2017) showed there are close correlations between the catches over time of each of the six neritic tunas. The high level of correlation amongst these species is likely to be because they are often caught together, due to difficulty with species identification and also because of the estimation procedures used to assign proportions of catch amongst the various species. Species-specific reporting has improved over time, leading to a lower level of correlation in more recent years.

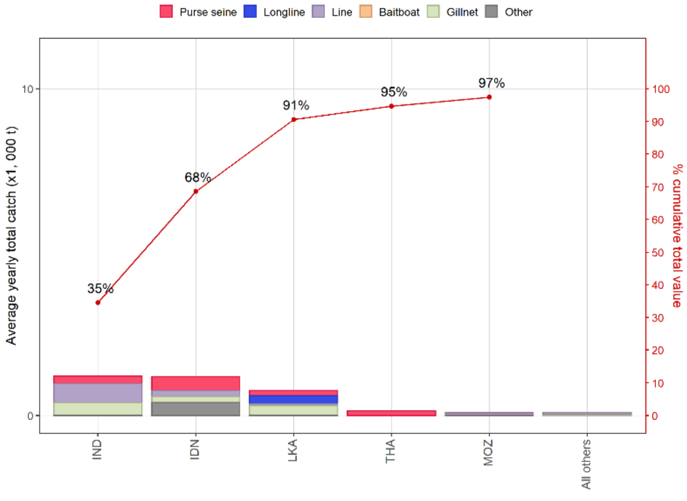

Figure 1: Average catches in the Indian Ocean over the period 2015-2022, by country. The red line indicates the (cumulative) proportion of catches of *A. rochei* by country.

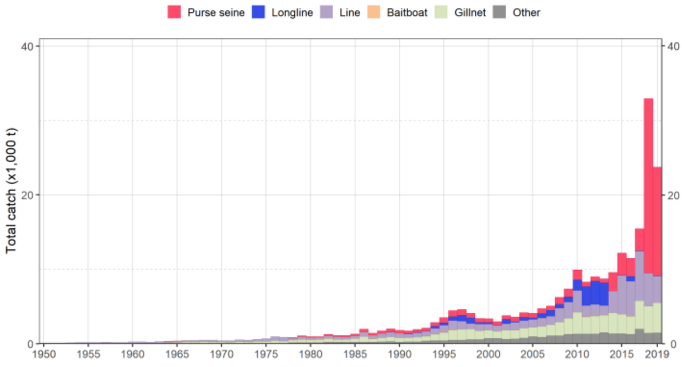

Figure 2: Annual catches of *A. rochei* by gear, 1950 – 2022 (IOTC database).

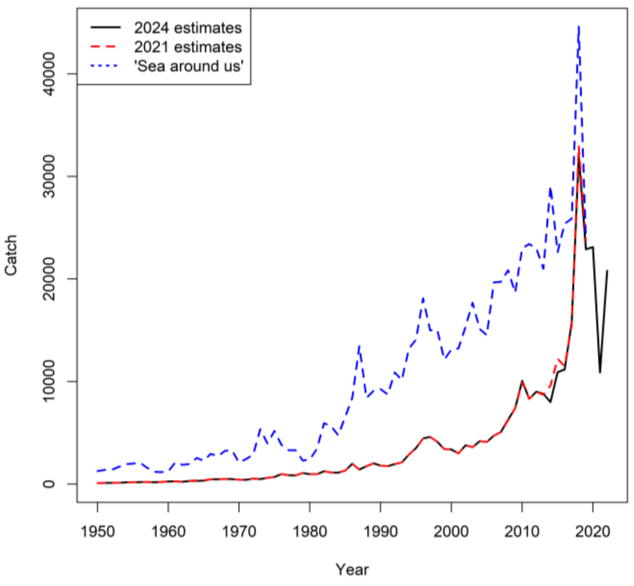

Figure 3: Revisions to IOTC nominal catch data for *A. rochei*.

Table 1. Catch data for *A. rochei* in the Indian Ocean, 1950-2022 (source IOTC Database)

Year	Catch (t)	Year	Catch (t)
1950	99	1987	1 418
1951	114	1988	1 744
1952	120	1989	2 021
1953	127	1990	1 797
1954	165	1991	1 744
1955	176	1992	1 951
1956	198	1993	2 119
1957	205	1994	2 880
1958	186	1995	3 515
1959	199	1996	4 454
1960	247	1997	4 595
1961	268	1998	4 121
1962	228	1999	3 407
1963	298	2000	3 372
1964	312	2001	2 991
1965	333	2002	3 788
1966	458	2003	3 602
1967	472	2004	4 179
1968	497	2005	4 111
1969	486	2006	4 713
1970	426	2007	5 078
1971	415	2008	6 282
1972	537	2009	7 392
1973	489	2010	10 074
1974	611	2011	8 303
1975	697	2012	9 009
1976	972	2013	8 803
1977	864	2014	7 995
1978	844	2015	10 903
1979	1 074	2016	11 175
1980	967	2017	15 756
1981	959	2018	32 065
1982	1 257	2019	22 901
1983	1 129	2020	23 102
1984	1 109	2021	10 883
1985	1 320	2022	20 794
1986	1 973		

4. Methods

4.1. C-MSY method

The C-MSY method of Froese et al. (2016) was applied to estimate reference points from catch, resilience, and qualitative stock status information for the bullet tuna. 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 – 2019, 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.

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

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

The prior range for *r* was estimated using the life history module (LHM) developed by Edwards (2016). The model implements Monte Carlo sampling of life history parameter distributions, with iterated solving of the Euler-Lotka equation (McAllister et al. 2001). The population parameters of *A. rochei (*including growth, natural morality, maturity, and length-weight relationship) are based on values as collated by Robinson (2015). The estimated distribution of r suggested a credible range of 0.5 – 2.0 for *A. rochei* (Figure 4). Martell and Froese (2012) proposed a classification of the stock resilience levels 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, *A. rochei* has a medium level of resilience and a range of 0.2 – 0.8 (Froese and Pauly 2015). For the analysis, the LHM estimates of 0.6 – 2.0 was used a reference case as they are based on existing parameter values. The FishBase resilience estimates of 0.2–0.8 was used as a sensitivity in the previous assessment. 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 (0.4–0.8), using a set of rules based on the trend of the catch series (see Froese et al. (2016) for details). The prior range for the depletion level can also be assumed optionally for an intermediate year, but this option was not explored in this report.

With this approach, the prior range for the depletion level in 2019 was determined to be medium. The prior ranges used for key parameters are specified in 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.

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: Prior ranges used for *A. rochei* in the C-MSY analysis reference model

Species	**Initial B/K**	**Final B/K**	***r***	***K (1000 t)***
Reference model	0.5–0.9	0.2–0.6	0.5–2.0	13– 207

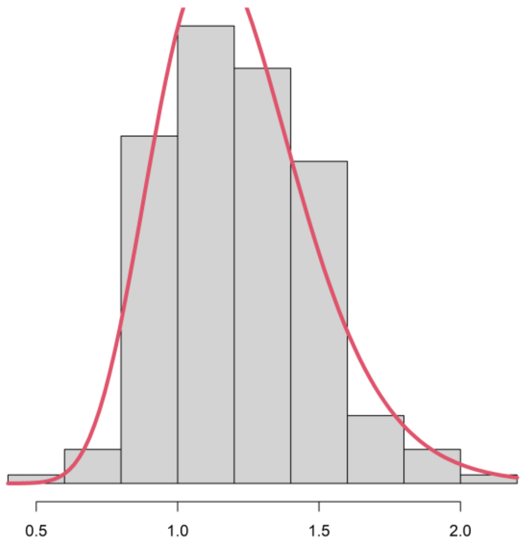

Figure 4: Estimated distribution of the population growth rate r for *A. rochei*, using the LHM module of Edwards (2016).

4.2. Length-based Spawner Potential Ratio (LB-SPR)

The LB-BTR method (Hordyk et al. 2014a) estimates the Spawning Potential Ratio (SPR) of a stock directly from the size composition of the catch. The SPR of a stock is defined as the proportion of the unfished reproductive potential left at any given level of fishing pressure (Hordyk et al. 2014b) and is commonly used to set target and limit reference points for fisheries. The $F_{40\%}$, i.e. the fishing mortality rate that results in SPR at 40%, is considered risk adverse for many species. The LP-BTR establish that how length compositions and spawning ratios are determined by fishing mortality and life history ratio, which are known to be less variance across species. The LP-BTR uses maximum likelihood methods to estimate relative fishing mortality (F/M) and selectivity-at-length that minimize the difference between the observed and the expected length composition of the catch and calculates the SPR (Hordyk et al. 2014a). The LB-SPR model requires the following parameters: an estimate of the ratio M/k (i.e. the individual values of the M and k parameters may be unknown), L^{∞} (and associated variance), and maturity-at-size. These parameters for *A. rochei* are obtained from Robinson (2015).

The length data used are those provided to the WPNT11 (IOTC-2023-WPNT13-DATA09-SFdata), which contains length samples by gear, fleet, year, month, and spatial area. For bullet tuna, catch samples were available from the line, gillnet, and purse seine fisheries. However, the samples from the line fishery are patchy and there is no sample from recent years. The purse seiners have caught mostly younger fish and are not suitable for the analysis as the LB-SPR model should be applied to fleet that target the adult portion of the stock. Therefore, the analysis used the length data from the gillnet fishery for 2016, 2017, and 2020.

5. Results

5.1. C-MSY method

Figure 5 shows the results of the reference model from the CMSY analysis. 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. 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 1.02–1.97 (mean of 1.42) while probable K values ranged from 36 100– 99 800 (mean of 60 000). 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 late 2000s.

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 neritic tuna species have not yet been defined, so the values applicable for other IOTC species are used. Management quantities (estimated means and 95% confidence ranges) are provided in Table 3, which shows an average MSY of about 21 200 t. The KOBE plot indicates that based on the C-MSY model results, bullet tuna is currently overfished (B2022/BMSY=0.92) and is subject to overfishing (F2022/FMSY = 1.12). The average catch over the last five years is higher than the estimated MSY (Table 3).

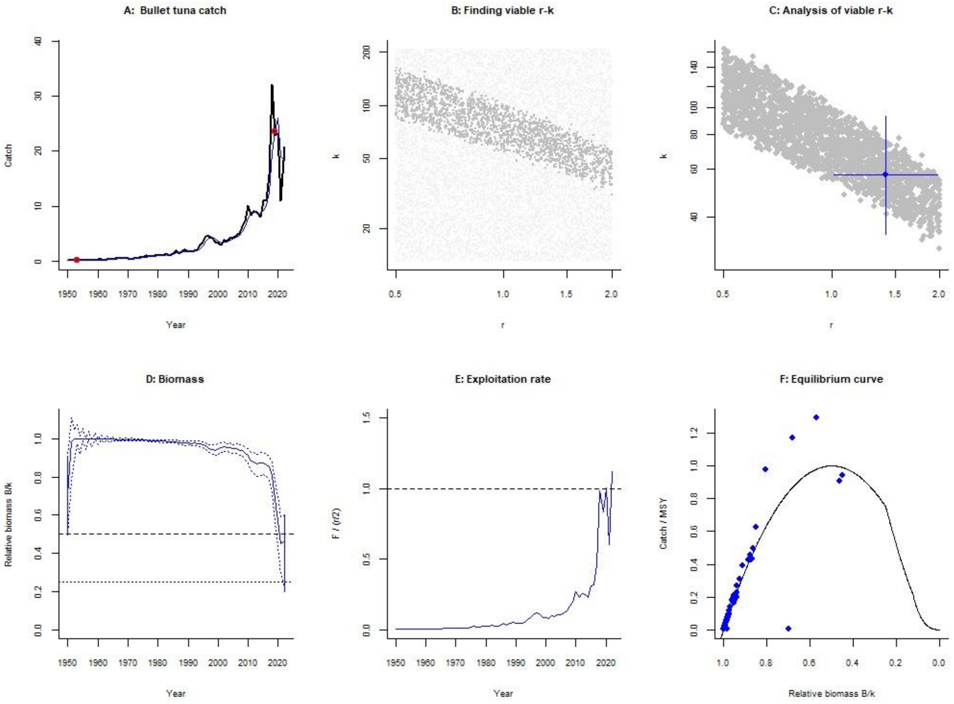

Figure 5. Results of CMSY reference model for bullet tuna.

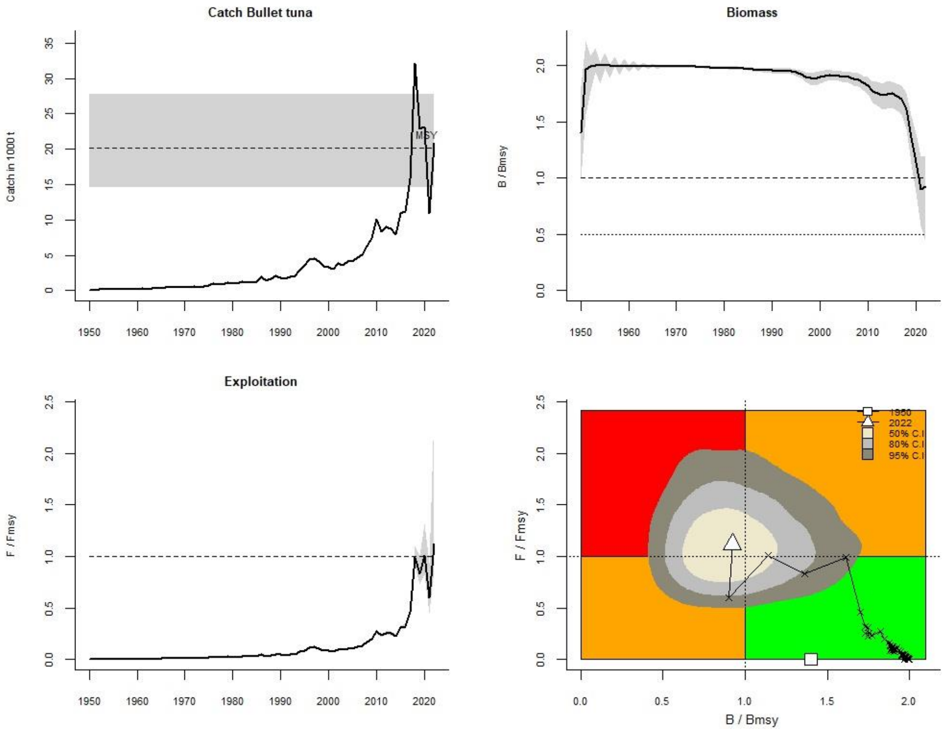

Figure 6. Graphical output of the CMSY reference model of bullet tuna for management purposes.

Table 3. Key management quantities from the Catch MSY assessment for bullet tuna. Geometric means (and plausible ranges across all feasible model runs). n.a. = not available. Previous assessment results are provided for comparison.

Management Quantity	2021 reference model	2024 reference model
Most recent catch estimate	23 719 t (2019)	20 794 t (2022)
Mean catch –recent 5 years	20 204 t (2015 – 2019)	21 950 t (2018 – 2022)
MSY (95% CI)	14 200 (8 740 –23 000)	20 100 (15 000 –27 800)
Data period used in assessment	1950 – 2019	1950 – 2022
F_{MSY} (95% CI)	0.71 (0.51- 0.99)	0.71 (0.51- 0.99)
B_{MSY} (95% CI)	20 000 (11 200 – 35 600)	28 500 (17 400 – 46 600)
$F_{current}/F_{MSY}$ (95% CI)	1.84 (1.41 – 3.91)	1.12 (0.87 – 2.42)
$B_{current}/B_{MSY}$ (95% CI)	0.91 (0.43 – 1.19)	0.92 (0.42 – 1.19)
$B_{current}/B_0$ (95% CI)	0.46 (0.21 - 0.60)	0.46 (0.21 - 0.60)

5.2. LB-SPR method

The LB-SPR provides a reasonable fit to the length distribution in 2016, 2017, and 2020 (Figure 7-left). The model estimated that there appears to be a shift towards younger fish in fishing selectivity (Figure 7-right). The fishing mortality was estimated to have reduced from 2016, 2017, and 2020 (Figure 7-right) whereas it was still several folds higher than the potential FMSY (≈0.87M was considered a reasonable approximation of FMSY for teleost, see Zhou et al., 2012). The Spawning potential ratio was estimated to be below 0.40 in 2016, 2017, and 2020 (the SPR of 0.4 is often considered a risk-averse target, see Hordyk et al. 2014a), suggesting the stock is depleted in relation to the risk-averse target.

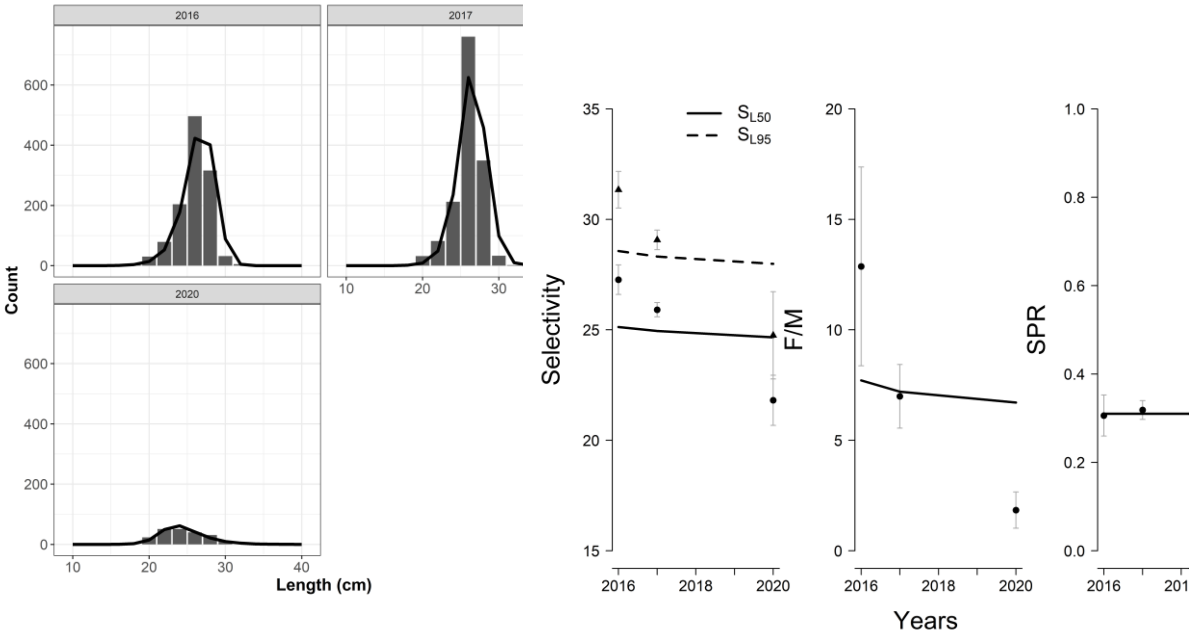

Figure 7: Results of LB-SPR method applied to the length samples from the gillnet fishery for bullet tuna: Fits to the length frequency in 2016, 2017, and 2020 (black dots) a; right – estimates (with 95% CI) of logistic selectivity parameter (a50 and a95), F/M, and Spawning Potential Ratio.

6. Discussion

In this report we updated the two data-limited methods in assessing the status of bullet tuna: C-MSY and LB-SPR. The C-MSY is based on an aggregated biomass dynamic model and requires only the catch series as model input and uses simulations to locate feasible historical biomass that support the catch history. Similar to the previous assessment, estimates from the C-MSY model suggested that currently the stock of bullet tuna in the Indian Ocean is overfished (B2022 < BMSY) and is subject to overfishing (F2022 > FMSY), and the estimates would be more pessimistic if the stock productivity is assumed to be less resilient. The overfishing stock status is clearly a result of the drastic increase of the catches in 2018 and 2019 which doubled the catch in 2017. While there is a significant reduction of catch in 2021, the catch increased sharply again in 2022. Despite the substantial uncertainties described throughout this paper, the overfished stock status suggests the higher catches may not be sustained.

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. 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 on estimates of stock status.

The analysis also demonstrated an application of the LB-SPR method for estimating Spawning Potential Ratio, a well-established biological reference point, by utilizing life history parameters and length composition data. The LB-SPR has potential to provide a cost-effective tool for the assessment of IOTC neritic tuna stocks considering length data are one of the easiest and most affordable data to collect for many small-scale, data-poor fisheries (Hordyk et al. 2014a). In contract to the C-MSY method (and other catch only methods), which requires accurate and complete catch statistics, the LB-SPR only requires the length frequency data to be representative, which is more likely to achieve for many IOTC neritic tuna species.

Estimates of stock status from the LB-SPR method is not directly comparable to the C-MSY as they have assumed very different target reference points. Nonetheless, the SPR estimated by the LB-SPR method (0.31) was much below the $SPR_{40\%}$, and fishing mortality is much higher than FMSY, corroborating the conclusion of the C-MSY which suggested that the stock is currently overfished and is subject to overfishing.

One concern is that the LB-SPR model assumes asymptotic selectivity and the results are shown to be sensitive to the assumption (as the model interprets the absence of the large individuals from the size structure as evidence for a high level of exploitation, see Hordyk et al. (2014a)). In the analysis, the LB-SPR was applied to the length samples from the gillnet fishery. Although gillnet is typically featured a dome-shape selectivity, the doming is unlikely to be severe for bullet tuna, given the relatively small size of this species ($L^{\infty} \approx 40cm$). Further, Hordyk et al. (2014a) showed that the species with high M/K ratio (such as bullet tuna) are less sensitive to the doming, as fewer individuals live long enough to reach asymptotic size such that a smaller fraction of the population is affected by the dome-shaped selectivity.

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