Assessment of Indian Ocean Frigate tuna (*Auxis thazard*) 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 frigate tuna (*Auxis thazard*). Fu (2021) provides a preliminary assessment of *A. thazard* 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 line fishery.

2. Basic Biology

Frigate tuna (*Auxis thazard*) is a highly migratory epipelagic species inhabiting neritic and oceanic waters of the tropical Indo-Pacific and Atlantic oceans (Froese & Pauly 2016). Frigate tuna are primarily taken by line (longline, hand line, troll line) and gillnet gear in coastal waters, and are also an important bycatch for industrial purse seine vessels. Catches are concentrated in Indonesia and to a lesser extent in India and Sri Lanka (Geehan & Pierre 2015). Most research on growth for this species derives from those countries, particularly India, and is predominately based on length-frequency studies (Robinson 2015).

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. thazard* are lower than some of the other neritic species, with a total catch of only 105 637 t reported in 2022 (Table 1). Indonesia, Iran, Pakistan, India and Sri Lanka all have important fisheries for *A. thazard* and the catches are largely dominated by gillnet and line fisheries (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 frigate tuna nominal catch series (Figure 3).

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.

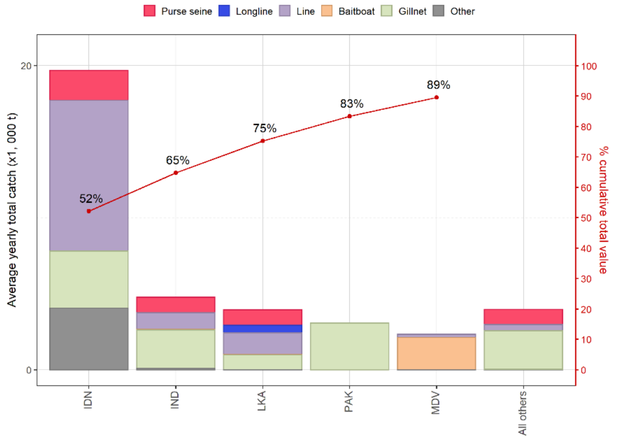

Figure 1: Average catches in the Indian Ocean over the period 2015-2019, by country. The red line indicates the (cumulative) proportion of catches of *A. thazard* by country.

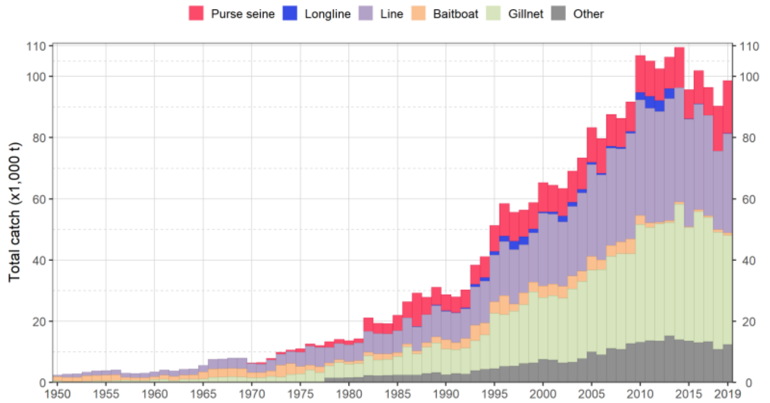

Figure 2: Annual catches of *A. thazard* by gear, 1950 – 2019 (IOTC database).

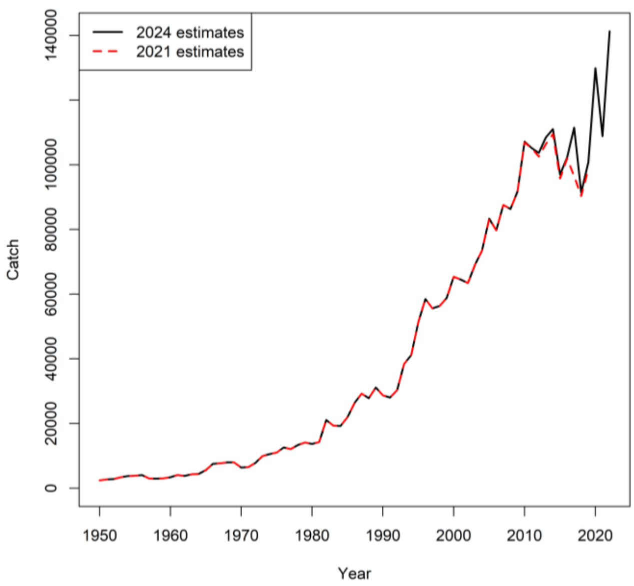

Figure 3: Revisions to IOTC nominal catch data for *A. thazard* (datasets used for the 2024 and 2021 assessments).

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

Year	Catch (t)	Year	Catch (t)
1950	2 422	1987	29 233
1951	2 723	1988	27 809
1952	2 822	1989	31 124
1953	3 381	1990	28 698
1954	3 757	1991	27 994
1955	3 853	1992	30 301
1956	4 035	1993	38 414
1957	3 014	1994	41 114
1958	2 919	1995	51 364
1959	3 037	1996	58 470
1960	3 393	1997	55 588
1961	4 087	1998	56 322
1962	3 784	1999	58 828
1963	4 302	2000	65 370
1964	4 428	2001	64 489
1965	5 604	2002	63 420
1966	7 518	2003	69 080
1967	7 698	2004	73 469
1968	7 964	2005	83 334
1969	7 977	2006	79 715
1970	6 359	2007	87 592
1971	6 501	2008	86 323
1972	7 829	2009	91 760
1973	9 907	2010	107 142
1974	10 549	2011	105 191
1975	11 019	2012	103 672
1976	12 566	2013	108 450
1977	12 110	2014	111 016
1978	13 337	2015	96 983
1979	14 109	2016	102 258
1980	13 695	2017	111 474
1981	14 292	2018	91 380
1982	21 077	2019	100 786
1983	19 367	2020	129 858
1984	19 214	2021	108 852
1985	21 944	2022	141 279
1986	26 357		

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 frigate 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 – 2018, 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. thazard (*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 0.6 –1.8 for *A. thazard* (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. thazard* has a medium level of resilience and a range of 0.2 – 0.8 (Froese and Pauly 2016). For the analysis, the LHM estimates of 0.6 – 1.8 was used a reference case as they are based on existing parameter values where as FishBase resilience estimates of 0.2–0.8 was used as a sensitivity. 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. thazard* 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	0.6–1.8	59 – 708

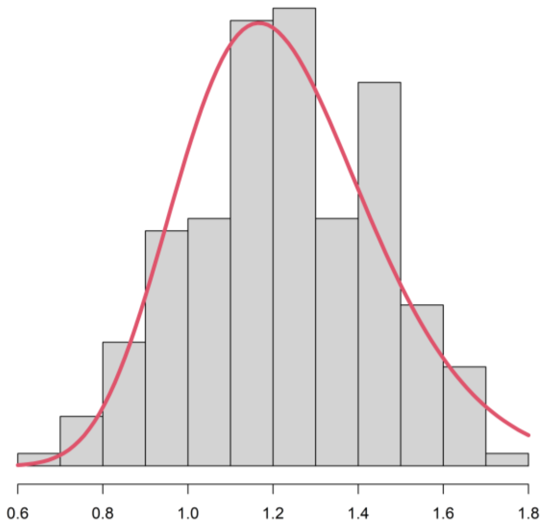

Figure 4: Estimated distribution of the population growth rate r for *A. thazard*, using the LHM module of Edwards (2016).

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. thazard are obtained from Robinson (2015).

The length data used are those provided to the WPNT11 (IOTC-2020-WPNT10-DATA09-SFdata), which contains length samples by gear, fleet, year, month, and spatial area. For frigate tuna, catch samples were available from the line, baitboat, gillnet and purse seine fisheries. The analysis used the length samples from the line fishery for 2017 and 2018. The baitboat accounts for a small fraction of the total catches for frigate tuna; the gillnet is likely to feature a dome shaped selectivity; the small purse seiners appeared to have caught mostly younger fish (the LB-SPR model should be applied to data from the fleet that target the adult portion of the stock).

1. Results

1.1. 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 1.05–1.77 (mean of 1.36) while probable K values ranged from 222 000 – 460 000 (mean of 320 000). 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 110 000 t. The KOBE plot indicates that based on the C-MSY model results, frigate tuna is currently not overfished (B2022/BMSY=1.04) but is subject to overfishing (F2022/FMSY = 1.24). The average catch over the last five years fluctuate around the estimated MSY (Table 3).

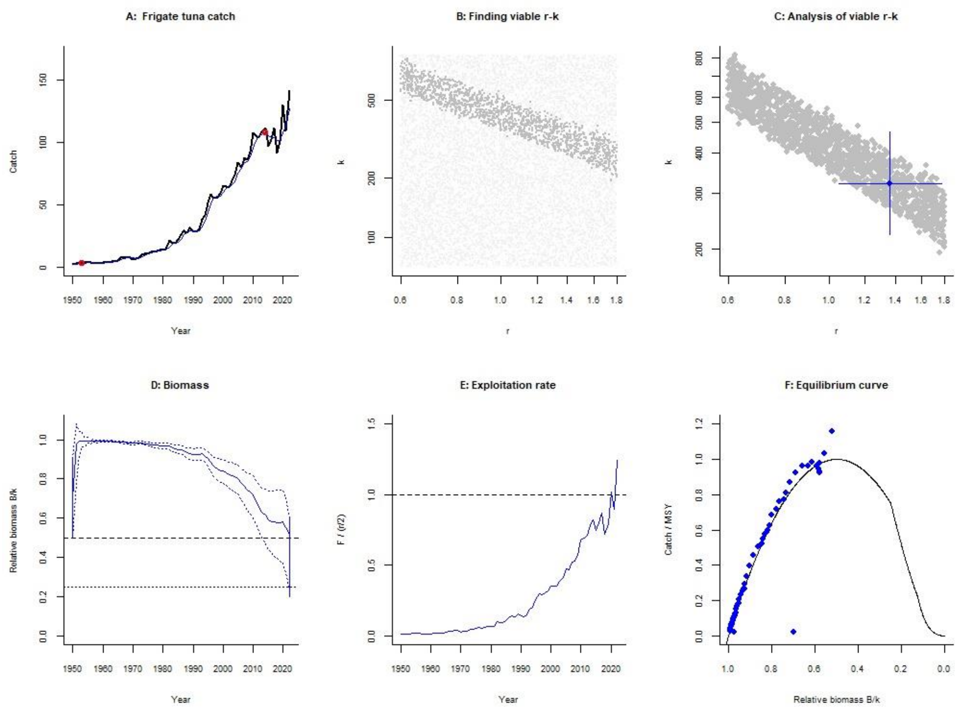

Figure 5. Results of CMSY reference model for frigate tuna.

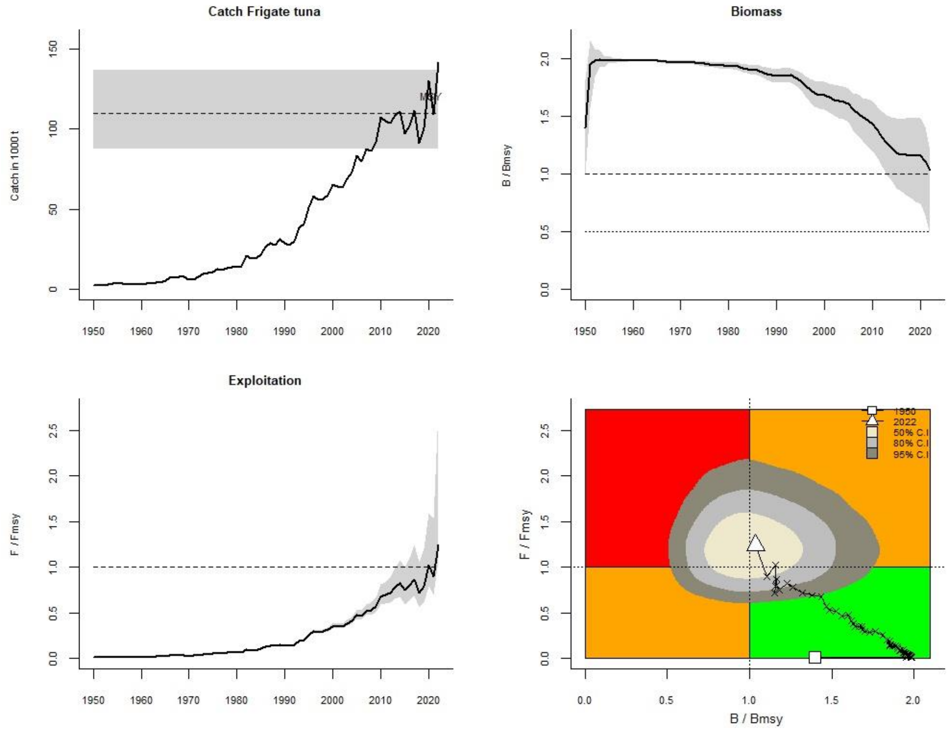

Figure 6. Graphical output of the CMSY reference model of frigate tuna for management purposes.

Table 3. Key management quantities from the Catch MSY assessment for frigate 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	98 761t (2019)	141 279 (2022)
Mean catch –recent 5 years	95 975 t (2015 – 2019)	114 431 (2018 – 2022)
MSY (95% CI)	102 000 (83 100 –125 000)	110 000 (87 800 – 137000)
Data period used in assessment	1950 – 2019	1950 – 2022
F_{MSY} (95% CI)	0.682 (0.53- 0.89)	0.682 (0.53 – 0.89)
B_{MSY} (95% CI)	149 000 (104 000 – 215 000)	161 000 (111 000 – 234 000)
$F_{current}/F_{MSY}$ (95% CI)	0.92 (0.76 – 2.03)	1.24 (1.08 – 2.73)
$B_{current}/B_{MSY}$ (95% CI)	0.99 (0.45 – 1.19)	1.04 (0.47 – 1.19)
$B_{current}/B_0$ (95% CI)	0.49(0.22 – 0.60)	0.52 (0.24 – 0.60)

1.2. LB-SPR method

The LB-SPR provides a reasonable fit to the length distributions in 2017–2020 (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 whereas the SPR has also decreased from 2018 to 2020 (Figure 7-right). The spawning potential ratio was estimated to be around 0.50 over 2017 – 2020, which is higher than the commonly assumed risk-averse target of 0.4 (see Hordyk et al. 2014a), suggesting the stock is in a healthy status in recent years (with data up to 2020 this method assumes a different target to the C-MSY method).

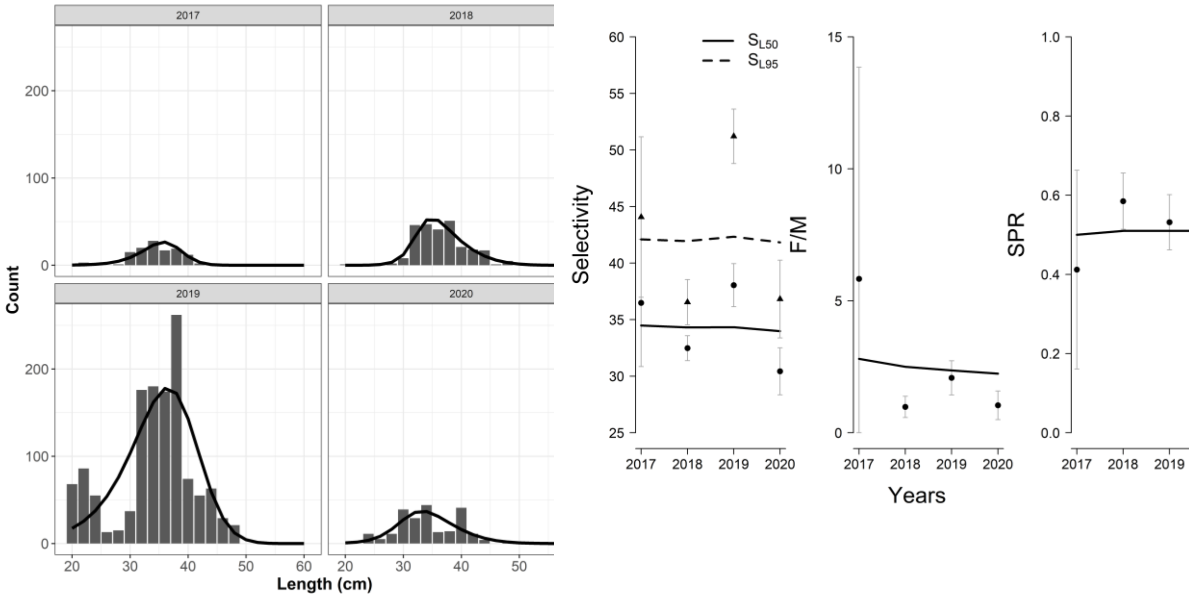

Figure 7: Results of LB-SPR method applied to the length samples from the line fishery for frigate tuna: Fits to the length frequency in 2017 – 2020 (black dots) a; right – estimates (with 95% CI) of logistic selectivity parameter (a50 and a95), F/M, and Spawning Potential Ratio.

2. Discussion

In this report we have explored two data-limited methods in assessing the status of frigate 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. Estimates from the C-MSY model suggested that currently the stock of frigate tuna in the Indian Ocean is probably above the biomass target (B2022 > BMSY) and is currently subject to overfishing (F2022 < FMSY). The C-MSY estimated a mean MSY of approx. 110 000 t with a relatively wider range. Reported catches of frigate tuna in the Indian Ocean has increased considerably since the late 2000s, with recent catches being above 100,000 t. 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. 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 point. However, the SPR estimated by the LB-SPR can be considered as a measure of depletion, and for frigate tuna, the estimate of current SPR is about 0.50, which is very similar to the C-MSY estimate of 0.52, although the estimates are based on different dynamics for the two methods (the LB-SPR uses a spawner-per-recruit whereas the C-MSY estimate is based on the Schafer dynamic model).

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