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Original Article

Understanding fishery interactions and stock trajectory of yellowfin tuna exploited by Iranian fisheries in the Sea of Oman

Morteza Eighani [1,*], Jason M. Cope[2], Paria Raoufi[3], Reza Abbaspour Naderi[4], and Pascal Bach[5]

[1] *National Institute of Aquatic Resources (DTU AQUA), Technical University of Denmark, Hirtshals 9850 North Sea Science Park, Hirtshals, Denmark*
[2] *NOAA Fisheries, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112, USA*
[3] *Fisheries Department, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan , Golestan 4913815739, Iran*
[4] *Iranian Fisheries Organization, Tehran NO. 236, Iran*
[5] *MARBEC, University of Montpellier, Sète 34200 CNRS, Ifremer, IRD, Sete, France*

**Corresponding author: tel: +45 71520219; e-mail: moei@aqua.dtu.dk*

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The predominant policy for remedying the world fishing crisis aims at maximum sustainable yield (MSY) by adjusting gear selectivity and fishing effort to maintain sustainable stock levels. The yellowfin tuna (*Thunnus albacares*) fishery in the Sea of Oman has experienced intense increases in removals since 1980, with particularly high levels since the 1990s. Here, we apply a statistical catch-at-age model to time-series of catches and fishery-dependent length composition data to obtain a preliminary and general understanding of the population dynamics of this stock since the start of the fishery in 1950–2019. Despite limited data, population models consistently indicate a sharp decline in population status since the beginning of the time-series across a variety of assumptions on stock productivity and life history. The gillnet fishery takes almost exclusively immature individuals, with high fishing intensity and removal rates. Both reference models indicate the population is essentially at the same relative stock status in 2019 (10% of unfished), but with very different future projections and higher absolute stock size when recruitment is estimated. The yellowfin tuna population in 2019 is below estimated MSY reference points (based either on unfished size or spawning output at MSY) for current relative stock size, and over the fishing intensity at MSY, indicating current overfishing. Adjusting the interactions of that fishery with the population, while continuing to collected biological composition data representative of each fleet in the fishery, will help mitigate current stock decline and provide the ability to refine future population status determination and forecasts through more informed stock assessments.

Keywords: data-limited, fisheries management, gear selectivity, model uncertainty, spawning output, stock assessment, tuna

Introduction

As top predators in the oceans, tuna populations play an important role in pelagic ecosystems while also being a major source of protein for humans worldwide (Gilman *et al.*, 2017; McCluney *et al.*, 2019). Large predatory fish such as tunas contribute to the well-being of fishing communities and food security, particularly in northern Indian Ocean countries such as Pakistan, Oman, Yemen, and Iran, helping to reduce poverty and hunger in the coastal regions of these countries (Eighani *et al.* 2018, 2019). Yellowfin tuna (*Thunnus albacares*) (YFT) is one of the most targeted tuna species in the Indian Ocean (Somvanshi, 2002; Zhang *et al.*, 2013), with an estimated 400000 t landed in 2019. In 2017, the catch of YFT in Iran exceeded the national catch of any other country in the Indian Ocean (IOTC, 2019), with Iran's catch having roughly tripled from 19482 t in 2008 to 56121 t in 2017. This ever-increasing catch trend is largely driven by the elevated demand for seafood in Iran's domestic market, fueling a massive build-up in Iran's tuna fisheries. Yet, despite the growing socioeconomic importance of YFT in Iran, exploitation rates remain unregulated in artisanal fisheries.

The YFT is listed as "near threatened" on the IUCN Red List of Endangered Species (IUCN, 2016). While YFT stocks in the Western and Central Pacific are experiencing fishing rates below F_{MSY}, and stock biomasses in the Atlantic and Eastern Pacific are not below limits, the YFT in the Indian Ocean is perceived to be overfished and at risk of collapse given current harvest rates (IOTC, 2019; Winker *et al.*, 2019). In 2015, this stock was determined to be overfished and subject to overfishing, with 94% certainty that this was the case (IOTC, 2015). The following year, another stock assessment returned slightly more optimistic results, with a 67.6% certainty that the stock was both overfished and subject to continued overfishing (IOTC, 2016). IOTC's interim plan required Iran to reduce YFT catches by 10%, based on 2014 levels (IOTC, 2016; Resolution 16/01) corresponding to a threshold of 30000 t. In spite of these assessments of the stock as a whole, the sustainability of the YFT harvest within Iran's exclusive economic zone (EEZ) remains unknown. Left unregulated, overfishing could lead to depletion and reduced catches, impacting food security and the livelihoods of the fishing communities in Iran, especially given YFT is predominantly fished by and is a crucial species for the artisanal sector (Kaymaram *et al.*, 2014; IOTC, 2018a).

The Indian Ocean YFT stock assessment conducted by the Indian Ocean Tuna Commission currently assumes a single stock for the entire Indian Ocean, though the appropriate spatial structure for the assessment remains uncertain. A total of 54688 YFT were released by the RTTP-IO programme, with a reported 9916 tag recoveries (Fu *et al.*, 2018). Non-reporting of tagging data is estimated at 13% for YFT in the Indian Ocean (Gaertner and Hallier, 2015), and thus not an overwhelming degree to significantly bias interpretation. Tagging recovery information is inconclusive, as tag recoveries of the RTTP-IO provide evidence of large movements of YFT within the western equatorial region, but very few observations of large-scale transverse movements of tagged YFT. This may indicate that the western and eastern regions of the Indian Ocean support relatively discrete sub-populations of YFT (Langley, 2015). Almost all of the tags released in Region 1 were recovered in the home region (Fu *et al.*, 2018). Oman-tagged tuna are peculiar as all tagged tuna are YFT and show a limited time at liberty (143 d). The high percentage of local recoveries is responsible for this short time at liberty. Most of the recoveries came from the purse-seine fisheries only 140 d after initial tagging (Hallier and Million, 2009). Low tag recovery rates are reported from Iranian fisheries (mainly the gillnet fleet), and no recoveries from the longline fisheries in the Sea of Oman (Hallier and Million, 2009). Genetic analysis investigating population delineation of YFT offer a little more evidence for spatial structure. Mitochondrial DNA D-loop analysis identified three discrete populations of YFT in the Indian waters (Northern Arabian Sea, Lakshadweep Islands, and the rest of the Indian seas; Kunal *et al.*, 2013). A larger study with broader sampling oceanic sampling using whole-genome sequencing in concert with a draft genome assembly also indicated the possibility of a distinct YFT population in the Arabian Sea in addition to Atlantic and Indo-Pacific populations (Barth *et al.*, 2017; Varghese *et al.*, 2019).

The possible existence of distinct YFT populations within the Indian Ocean raises important management considerations for this species and provides the basis for the exploratory work that we present. Fundamental to fish stock assessment is identifying proper management units and subsequent measures to maintain resource sustainability. Spatial resolution of a stock assessment depends on biological and local population response to fishing (Cope and Punt 2009, 2011). Determination of stock structure is of prime importance to the management of any fishery, since each stock within the overall species metapopulation can possess novel genetic, physiological, behavioural, and other characters that promote distinct differences in life history traits (Reiss *et al.*, 2009).

Given the suggested genetic population structuring, vast size of the Indian Ocean, differential regional fishing histories, and the migration rate inferences that have been made from tagging studies to date, it seems unlikely that rapid mixing processes across the whole basin are sufficient to homogenize population dynamics, thus making regional assessments worthy of consideration to track local depletion events (Cope and Punt, 2011). Given the uncertainties explained above and the large localized catch of the Iranian fleet, it is arguable that a local assessment for an Iranian-area stock of YFT is worth consideration.

In this study, we describe fisheries targeting the YFT in Iran's EEZ of the Sea of Oman and examine their size compositions from the four primary fishing grounds in the region. We apply a statistical catch-at-age model to time-series of catches and fishery-dependent length composition data to obtain a preliminary and general understanding of the population dynamics of this stock. Our study may aid in steering management efforts in Iran towards the sustainability of the YFT in the Indian Ocean as a whole.

Yellowfin tuna catch trend

YFT landings generally fluctuated between 20000 and 60000 t until the early 1980s where landings rose steadily. In 1993, landings of YFT grew to over 400000 t (Figure 1b). This sudden increase was mostly due to the rapid development of purse-seine, gillnet, and longline fisheries in the region. Annual landings reached an all-time high of 527602 t in 2004, followed by sharp decline from 2007 to 2011 that occurred as a result of the threat posed by piracy in the western Indian Ocean during this time. The YFT catch in Iran's EEZ increased gradually to about 20000 t in the early 1990s and rapidly to 40000–50000 t from the early to mid-2000s (Figure 1a). However, catches dropped again after that, but then steadily climbed through 2019. The initial increase was mostly due to the introduction of additional fishing vessels in the early 1990s mainly targeting YFT.

Due to the high market demand in Iran, YFT is harvested using a variety of fishing gear types. It has a major commercial importance to the income of local fishers and the supply chain involved (Hosseini and Kaymaram, 2015). Unlike other fishing regions of the Indian Ocean, the gillnet fishery in the Sea of Oman accounts for the majority of YFT landings. On average, over the period 1950–2018, gillnets were responsible for around 75% of YFT catches, followed by purse-seine fisheries at 10% (Figure 1). While the gillnet sector has remained dominant in Iran, the development of the purse-seine fishery started in 1992, with catches reaching 11000 t in 2004. The longline catch then started increasing due to an increase in the number of artisanal longline fishing vessels and reached almost 12000 t by 2018. Hook-and-line catches have increased gradually since 2005 and reached a maximum of about 700 t in 2018, but remain minor compared to the other sectors.

Description of fisheries targeting yellowfin tuna

Gillnet

Surface-set gillnets operate in Hormuzgan and Sistan–Baluchestan provinces throughout the year, with the stretched mesh size ranging from 100 to 120 mm twine material made entirely from conventional polyamide multifilament (manufacturer's specifications of 210D/36). The length of net panels range between 8 and 10 km. Active artisanal gillnetters comprise ca. 3160 vessels. However, the number of artisanal gillnet vessels has decreased in recent years and

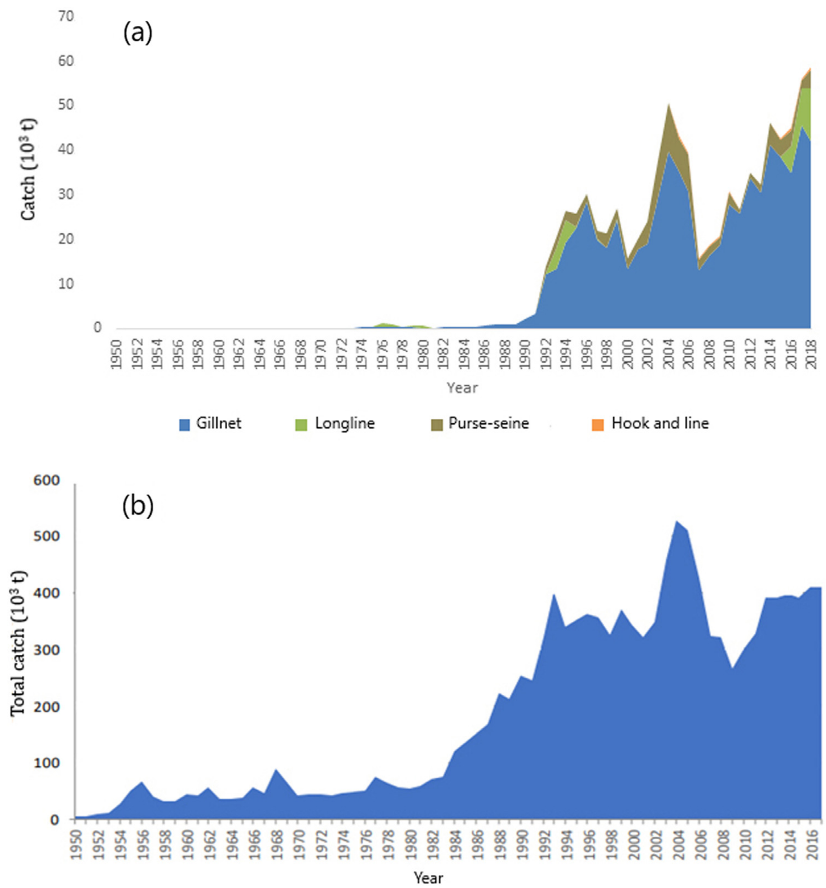

Figure 1. Catch trend of yellowfin tuna (a) harvested by Iranian fleet by gear (source: Iranian Fisheries Organization) and (b) in Indian Ocean (source: IOTC, 2019).

has been replaced by the longline fishery. Artisanal gillnetters use small fiberglass boats and dhows. The small boats vary in overall length from 5.5 to 7 m and are equipped with petrol engines of 48–55 hp, with a crew of about five fishers doing short cruises of 3 d on average. The overall length for dhows ranges from 18 to 32 m, and these are operated by diesel engines of 240–850 hp. The crew on dhows consists of 15 fishers on average, with a typical trip lasting ca. 30 d. The gillnet fishery continues throughout the year in both nearshore (mainly fiberglass boats) and offshore (mainly dhows) waters of Iran. Gillnets are the most common fishing gear used in Iran, generating more than 93% of the total fish catches. Gillnet selectivity is presumed to be dome-shaped, as it generally only includes fish < 100 cm.

Longline

The longline fishery targeting YFT in the Iran EEZ was effectively initiated in 1990s (though low catches existed in the 1970s) with an industrial Taiwanese style longliner owned by an Iranian company. The artisanal pelagic longline fishery started about four years ago and gradually expanded concomitant with a steady decline in the gillnet sector. Longline fishing gear consists of a standard monofilament polyamide mainline of 3-mm diameter (∼25-km long; stored on a drum), with four branch lines between floats. Branch lines are connected with the main line by a snap clip. A swivel is used to connect the branch line to the snap clip to avoid twisting. The maximum depth of the mainline at the centre of a basket is 78 m. Common bait types are live sardine (*Sardinella longiceps*) and Indian mackerel (*Rastrelliger kanagurta*) at a size of 25–30 cm. The common hook type is a circle hook in sizes ranging from 11/0 to 14/0. Active artisanal longliners include about 950 dhows and 1350 fiberglass boats, with 20000 fishers involved in this fishery, mostly in Sistan–Baluchestan Province. As with the gillnet fleet, the fiberglass boats used vary in overall length from 5.5 to 7 m and are equipped with petrol engines of 48–55 hp doing daily cruises with four fishers on board. The overall length for dhows ranged from 18 to 32 m, operated by diesel engines of 240–850 hp with 12 fishers on board staying 7 d at sea on average. The artisanal longline fishery is active throughout the year both in nearshore (mainly fiberglass boats) and offshore (dhows) waters of Iran. Longline fishery selectivity is presumed logistic (i.e. S-shaped or asymptotic) as this fishery may include the biggest fish available; and there is no indication that there is a drop off in selectivity at the largest sizes.

Purse-seine

Purse-seine operations started in 1992 in Iran. The tuna purse-seine fishery is the only industrial fishery in Iranian waters of the Sea of Oman. Iranian purse-seiners have a length overall around 99.5 m and are equipped with a global positioning system (GPS), sonar, echosounder, and a purse-seine net and skiff boat. The purse-seine net has a floating line about 1886-m long and a lead line of

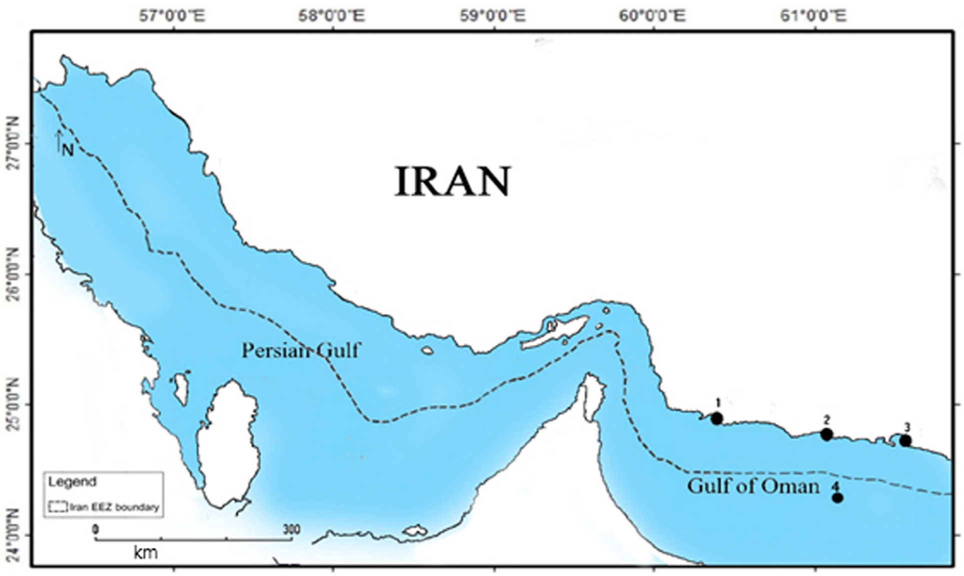

Figure 2. Sampling fishing ports for the present study in the southern coastline of Iran. The filled circles indicate the sampling sites: 1. Jask; (Hormuzgan Province); 2. Konarak; 3. Beris and Pasabandar; (Sistan–Baluchestan Province); 4. Offshore waters. The black dashed line represents Exclusive Economic Zone.

2026 m. The maximum height of the net (stretched net depth) is 210 m and stretched mesh size varies between 16 and 18 cm. A purse-seine is operated only in offshore waters with target tuna aggregations around fish aggregative devices (FADs). Currently, five purse-seiners targeting YFT operate in the offshore waters of Iran. The purse-seine fishery selectivity is also presumed logistic (i.e. S-shaped), as this fishery may include the biggest fish available.

Hook and line

Tuna hook and line (HL) is a fishing gear composed of a single vertical line with one barbed J-style hook in size ranging from 3/0 to 6/0 at the distal point. If several barbed hooks are used, branch lines are connected along the mainline at regular intervals. Most fishers use nylon (polyamide) for their HL. HL can be set and hauled either manually or by a mechanized reel. It is operated by simply dropping the baited hook to the depths at which tuna feed. Fishers generally use natural baits such as squid (*Uroteuthis duvaucelii*), sardine, and Indian mackerel. The HL gear is, in general, operated from boats, canoes, and other small decked or undecked vessels, without any special features for gear handling, with the exception of hand or mechanized reels. Tuna HL fishing is a seasonal practice and is carried out only in coastal waters of Sistan–Baluchestan Province. Currently, 1645 HL fishing vessels targeting YFT operate in the coastal waters of Iran. The catch harvested by this fishery is minimal and not included in the model.

Methods

Dataset of catch and length frequencies

Catch data were collected during the annual Iran Fisheries Organization (IFO) surveys from logbook data from 1950 to 2018. Removals prior to 1950 were assumed to be small relative to the contemporary catch history and, therefore, were not included in the population modelling. Length frequency data were collected at four sampling localities including one landing site in Hormuzgan Province, two landing sites in Sistan–Baluchestan Province, and one in the offshore waters between the Persian Gulf and the Sea of Oman coastlines (Figure 2). Georeferenced data on catch are not available, but from interviews with fishers, we were able to roughly locate the fishing grounds relative to landing sites. Information on technical characteristics of each gear, operation, and length frequency of target species was collected during five years from a number of sampled vessels from January 2015 to December 2019. Catch data were collected in each landing site by stratified random sampling by the port samplers. In this way, catches from dhows and other classes of fishing vessels were selected randomly. Length-based metrics to provide information on the length of the catch (fork length) to the nearest cm and the range were calculated for each gear type.

Estimating population dynamics and stock trajectory

The integrated statistical (i.e. able to use multiple data types via component likelihood functions) catch-at-age (SCAA) modelling framework Stock Synthesis (see SS v.3.30.16; Methot and Wetzel, 2013 for fuller descriptions of modelling approach, parameter treatment options, and likelihood functions) was used to estimate the stock trajectory using the input data and fixed and estimated model parameters. Stock Synthesis is a well tested and established option for conducting SCAA, with a global user base. The SS-DL tool (https://github.com/shcaba/SS-DL-tool) is an environment designed to make accessible this powerful modelling framework while extending it across a variety of data availability scenarios, and was used to conduct all analyses and produce plots using the r4ss package (https://github.com/r4ss/r4ss).

The model was parametrized as one sex and one area, thus with no movement in or out of the assessed area. Catch and length data were used as primary data inputs, with the starting effective sample size set to a maximum of 200 for the year with the most length samples, and all other years set relative to 200 by the ratio of yearly samples to the maximum. The Dirichlet-multinomial was used to weight the length compositions in the model (Thorson *et al.*, 2017).

Table 1. Life history values and source for the yellowfin tuna stock in Iran.

Parameter	Symbol	Value (units)	Source
Asymptotic length	L_∞	183.2 cm	Kaymaram *et al.*, (2014)
		240 cm	IOTC, (2017)
Maximum age	A_{max}	6 years	Kaymaram *et al.*, (2014)
		9 years	IOTC, (2017)
Growth coefficient	k	0.45 $year^{-1}$	Kaymaram *et al.*, (2014)
Natural mortality	M	0.48 $year^{-1}$	Kaymaram *et al.*, (2014)
Theoretical age at zero length	t_0	−0.2 year	Kaymaram *et al.*, (2014)
CV at length	CL_{Lt}	0.1	Expert opinion
Length at maturity (50%)	$L_{50}\%$	85.5 cm	Nootmorn *et al.* ,(2005); Zhu *et al.*, (2008); Kaymaram *et al.*, (2014); Froese and Pauly, (2019)
		100 cm	IOTC, (2017)

Table 2. The mean fork length ($\bar{x}$) and standard deviation (s.d.), minimum and maximum sizes, and proportion of immature fish (<85 cm) calculated from length frequency samples of each fishing gear type carried out in 2015–2019.

Fishing gear	$\bar{x}$ (cm)	s.d. (cm)	Min. size (cm)	Max. size (cm)	Proportion of immature fish (%)
Gillnet	84.8	13.7	36	166	52.5
Hook and line	104.7	9.7	79	128	3
Longline	111.2	22.3	54	171	6
Purse-seine	105.3	20.5	42	156	14.4

All life history values were fixed (Table 1), with the only estimated parameters being the natural logarithm of the initial recruitment size ($\ln R_0$) and the selectivity parameters, with recruitment estimated in one reference scenario. A six-parameter double-normal specification for selectivity was used (SS selectivity option 24), with five parameters being estimated for the dome-shaped gillnet fishery (one fixed), and two parameters being estimated for the longline and purse-seine logistic fleets (the other four fixed parameters ensure logistic behaviour on the descending limb of the function). This six-parameter form was used to make exploration of different selectivity forms easier, rather than specifying the alternative two-parameter form of the logistic model). Two reference models were explored based on whether recruitment was estimated for the entire removal history, each with a moderate stock–recruit relationship [recruitment compensation (i.e. steepness) set to 0.8]. Maximum likelihood estimation was used to estimate parameters and calculate derived model outputs, with the dominant likelihood component being the fits to the length composition data

$$L_f = \sum_{y=1}^{N_y} \sum_{a=1}^{A} n_{y,f}\ p_{y,f,l} \ln\left(p_{y,f,l}/\hat{p}_{y,f,l}\right), \quad (1)$$

where N_y is the sample index by year y, a is the age to accumulator age A, $n_{y,\ f}$ is the effective sample size by year y and fishery f, $p_{y,\ f,\ l}$ is the observed length proportion by year y, fishery f, and length bin l, and $\hat{p}_{y,\ f,\ l}$ is the expected length proportion by year y, fishery f, and length bin l.

Uncertainty

Uncertainty was expressed in two main ways. The first was within-model uncertainty calculated by inverting the Hessian matrix and expressing uncertainty as a normal distribution for all estimated parameters and derived outputs (Methot and Wetzel, 2013). Second, model specification error was explored by performing likelihood profiles for the steepness and natural mortality parameters. The likelihood profile approach fixes a given parameter at a pre-specified vector of values progressing from low to high. All other model specifications are kept the same; and the total likelihood value and derived quantities are captured. Natural mortality values from 0.3 to 0.6 with a step of 0.025 were explored. Steepness values from 0.3 to 1 with a step of 0.05 were also explored. Each method to quantify uncertainty was applied to the models with and without recruitment estimation.

Fisheries reference points

Defining reference points is critical for both interpreting and summarizing stock assessment results. While we do not define hard reference points here, we provide results in light of possible reference points used in other tuna assessments, as well as report estimated values for maximum sustainable yield (MSY and $1\text{–}SPR_{\text{MSY}}$) for context.

Results

A total of 170 082 YFT were sampled from commercial catches of longline, gillnet, purse-seine, and hook and line in four different areas of the western Indian Ocean from January 2015 through December 2019.

Yellowfin tuna fisheries

The most widespread fishery targeting tuna in the Indian Ocean is the gillnet fishery. In 2015–2019, the gillnet fishery targeted YFT in all the sampled locations. This large spatial distribution may explain why the catches in the gillnet fishery represent about 90% of the total YFT catch for all fishing gears over the past decade (Figure 1). The fishing grounds of hook and line and longline fisheries overlapped with gillnet landings in sites 2 and 3 during 2015–2019.

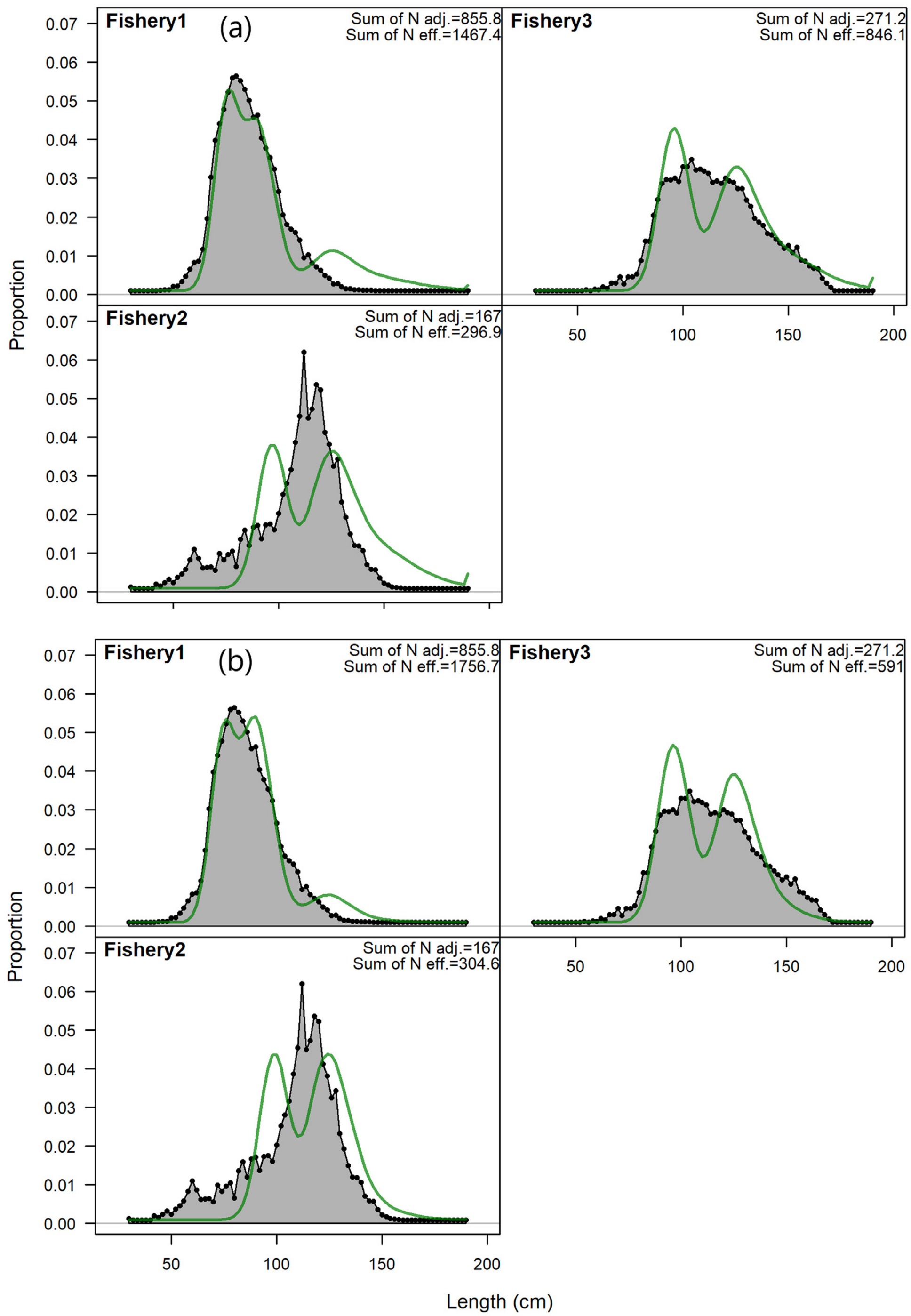

Figure 3. Composite length composition fits to the gillnet (Fishery 1), longline (Fishery 2), and purse-seine (Fishery 3) data for each reference model. (a) No recruitment estimated and (b) recruitment estimated.

The spatial extent of the purse-seine fishery did not overlap with any other gear type as it targeted YFT in offshore waters.

Length composition

The highest sampled mean length of the YFT was estimated from the longline length distribution (111.2 cm), whereas the lowest was estimated from the gillnet length distribution (84.8 cm) (Table 2). The length samples obtained from all other fisheries yielded a much higher mean length (>100 cm) than that obtained from gillnet fishery. The average length of YFT caught in the longline fishery was significantly larger than the average for those caught in the gillnet fishery ($P < 0.05$). The range of the length classes of the YFT was narrowest (79–128 cm) in the length samples of the hook and line fishery, unlike purse-seine and longline, which caught fish as small as 42 and 65 cm, and as large as 146 and 171 cm, respectively (Table 2). However, the largest fraction of immature fish (<85 cm) was caught by the gillnet fishery (52.5%), followed by purse-seine

(14.4%), while longline and hook and line catches contained very small fractions of immature fish (6 and 3%, respectively).

Model diagnostics

Both reference models are characterized by inverted Hessian, and thus estimate variances on parameters and derived outputs. This, along with reasonably low gradient values (<0.2) was indicative of converged models. These models were based on the best-fit model from 100 model runs, with jittered starting values (0.1 jitter values) of estimated parameters to ensure local minima were avoided. Not all jittered models returned the reference model (an important criterion expected of a properly jittered model), and no likelihood values less than the reference model were found, confirming a robust reference model despite varying to starting values.

Fits to the limited length data were adequate, with the best overall fits to the gillnet fishery (Figure 3). The longline and purse-seine fisheries showed poorer fits to the data, indicating some level of model misspecification that could not be captured in either recruitment or time-invariant selectivity estimation. Additional runs explored alternative data-weighting options using the Francis (Francis, 2011) or McAllister–Ianelli (McAllister and Ianelli, 1997) methods, both of which returned the same results as using the Dirichlet approach. There could be some systematic sampling issues causing biased sampling in these fisheries, which needs further attention. Overall and despite the issues with the longline/purse-seine data, the resultant selectivity curves were deemed reasonable for each of the fisheries, with the gillnet fishery showing prominent dome-shaped selectivity, and the other two gears being logistic and capturing larger individuals (Figure 4).

Population dynamics and stock status interpretation

Removals of YFT have increased steadily over the 1990–2018 period (Figure 1). The stock dynamics have shown a strong response to this increase in exploitation rates, with a demonstrative decline in spawning output over time regardless of the estimation of recruitment (Figure 5). Both reference models indicate that the population is essentially at the same relative stock status (10% of unfished; Table 3), but at a higher absolute stock size when recruitment is estimated (Figure 5).

One major difference in the population dynamics of the two reference models is the future trend of the population (Figure 5). Under a constant recruitment assumption, the population continues to decline under current fishing practices, whereas the population starts to increase if recruitments are estimated. The limited length composition data provide recruitment information only for the most recent years (Figure 5), with several estimated high recruitments in the last five years. This provides an injection of new biomass into the population, suggesting the potential for the population to halt the decline. Both reference models bookend two extreme states of nature—constant recruitment or high recruitment—but both still indicate that current stock status is very low. It is only under the assumption of large recent recruitments, that are estimated with large uncertainty, that the population can show the potential for recovery.

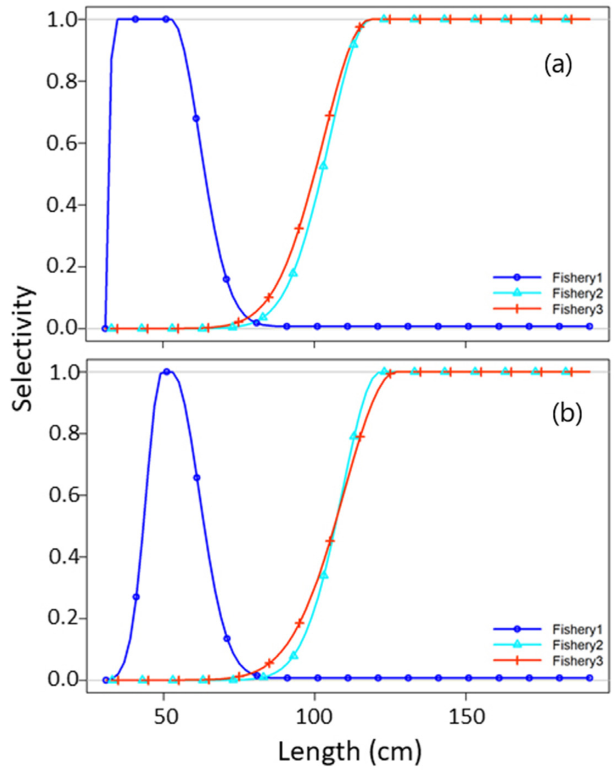

Figure 4. Selectivity estimates for the gillnet (Fishery 1), longline (Fishery 2), and purse-seine (Fishery 3) fisheries for each reference model. (a) No recruitment estimated and (b) recruitment estimated.

Model uncertainty

The reference model without recruitment estimation is highly constrained in its estimation of within-model uncertainty, while recruitment estimation shows large uncertainty in both absolute and relative spawning output in the historical period. The most informed period is unsurprisingly the years with length composition data; thus both models show high certainty that current stock status is low.

Likelihood profiles on natural mortality and recruitment compensation (steepness) offer further evidence of a stark population decline (Figure 6). There is little evidence in either model that natural mortality or steepness can be estimated (plot of parameter vs. –log likelihood value), as each model is best fit the higher the parameter value gets. This is often a sign of limited information in the data to inform the parameter (likely the situation here) or massive model misspecification. This is a common outcome in steepness profiles as two-way contrast in needed in biomass trends to gain information on this parameter (McAllister and Kirkwood, 1998). For what little signal there is contained in the data, most of it is coming from the gillnet fishery (Fishery 1, Figure 7), as it is the best-fit dataset, but dome-shaped fisheries are notoriously confounded with natural mortality. Despite the large range of values explored for both natural mortality and steepness, relative stock size never gets above 20% in 2019, even in the most biologically productive scenarios (Figure 6).

Fisheries reference points

The YFT population in 2019 is below estimated MSY reference points (based either on unfished size or spawning output at MSY)

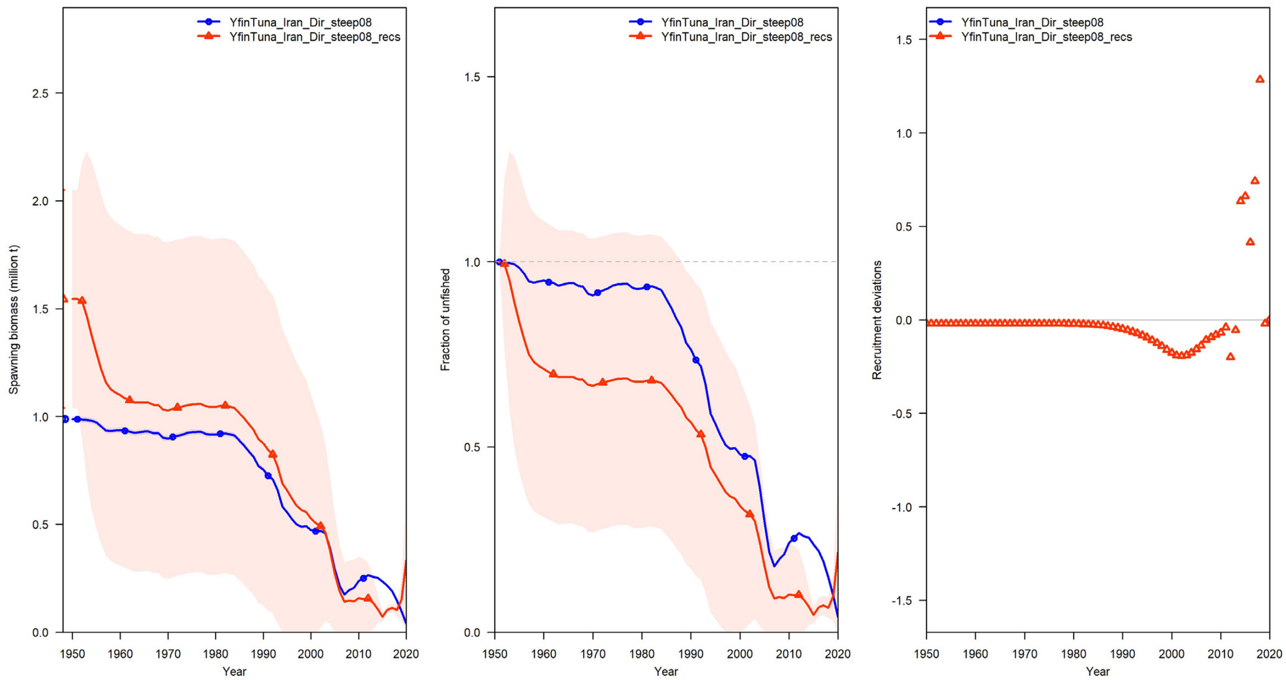

Figure 5. Comparison plots for (left to right) spawning output, relative spawning output, and recruitment deviations for yellowfin tuna off Iran. Blue with circles: no recruitment estimation. Red with triangles: recruitment estimation.

for current relative stock size, and above the fishing intensity at MSY (Table 3), indicating current overfishing. Projecting through 2020, only under the scenario of large recent recruitments is the fishing intensity below the MSY limit, but less than the relative spawning biomass at MSY (28%). If 20% is used as a limit spawning biomass, there is a high probability that the current status of YFT is below this value.

Discussion

Though the socio-economic importance of YFT is growing in Iran—which currently harvests the largest amount of YFT in the Indian Ocean—little is known about its fisheries, their catch composition, and the historical patterns of biomass and exploitation rates. The present study showed that the gillnet fishery catches by far the largest proportion (toggle between 75 and 90%) of YFT catch in Iran. Further, the current spawning output is below the MSY and MSY-proxy fisheries reference points, while fishing intensity is above those references.

The historical YFT trajectory shown in this study is consistent with that estimated by earlier reports which predicted that biomass and exploitation rates were unsustainable (Lee *et al.*, 2013; Langley, 2015; Fu *et al.*, 2018; Urtizberea *et al.*, 2019), and the most recent report shows that the stock is overfished and is experiencing excessive exploitation rates in the Indian Ocean (IOTC, 2018a; Winker *et al.*, 2019). Fu *et al.*, (2018) reported that spawning biomass was below SB_{MSY} ($SB_{2017}/SB_{MSY} = 0.87$) and fishing mortality was above F_{MSY} ($F_{2017}/F_{MSY} = 1.12$). Most sensitivity model options estimated that the stock is in an overfished state ($SB/SB_{MSY} < 1.0$) and that overfishing is occurring ($F/F_{MSY} > 1.0$), although the extent of the stock depletion varies considerably amongst the model options (Fu *et al.*, 2018). Total annual recruitment for the Sea of Oman and Arabian Sea was estimated at 64% (Langley, 2015) and 73% (Urtizberea *et al.*, 2019) in previous assessments. Recruitment within the western region (R1) is characterized by relatively high recruitment during the mid-1980s and late 1990s–early 2000s and lower recruitment during the early 1990s and particularly low recruitment during 2004–2006 (Langley, 2015). Recruitment in Region 1 was above average during 2009–2014. These trends in recruitment also drive the trend in total recruitment for the Indian Ocean.

The current stock size is likely severely depleted (estimated depletion in 2019 relative to an unfished population < 20%), with the high exploitation rates continuing to threaten the sustainability of the stock. The level of biomass relative to MSY ($SB_{MSY}/SB_0 = 0.35$) was also low and similar to other studies (e.g. Lee *et al.*, 2013; Langley, 2015). The lack of fisheries regulations is equally alarming, particularly given that the market demand for YFT is unlikely to diminish in the near future. By the industry's own admission, it has been difficult to determine a sustainable catch for Indian Ocean YFT. Scientists recommended in 2015 that a 20% reduction in catches was necessary to give the stock a 50% chance of recovery by 2024 (IOTC, 2018b).

Targeting sizes around or larger than size at maturity may result in the largest long-term yields in the future (this is the size where yield per recruit is optimized; Prince and Hordyk, 2019). However, a large fraction of the gillnet fishery catches consist of immature fish (52.5%), and gillnets have the highest exploitation rates among the modelled fleets, with catches still increasing. Subjecting the stock to high exploitation rates while retaining small and immature fish can result in recruitment overfishing, where recruitment is expected to fall linearly as biomass declines (Walters and Maguire, 1996). Fishery selectivity should, therefore, avoid catching smaller individuals that may not have spawned (Svedang and Hornborg, 2014). The link between higher selectivity and induction of individual density-dependent growth may have implications for MSY-based approaches, particulaly when increased selec-

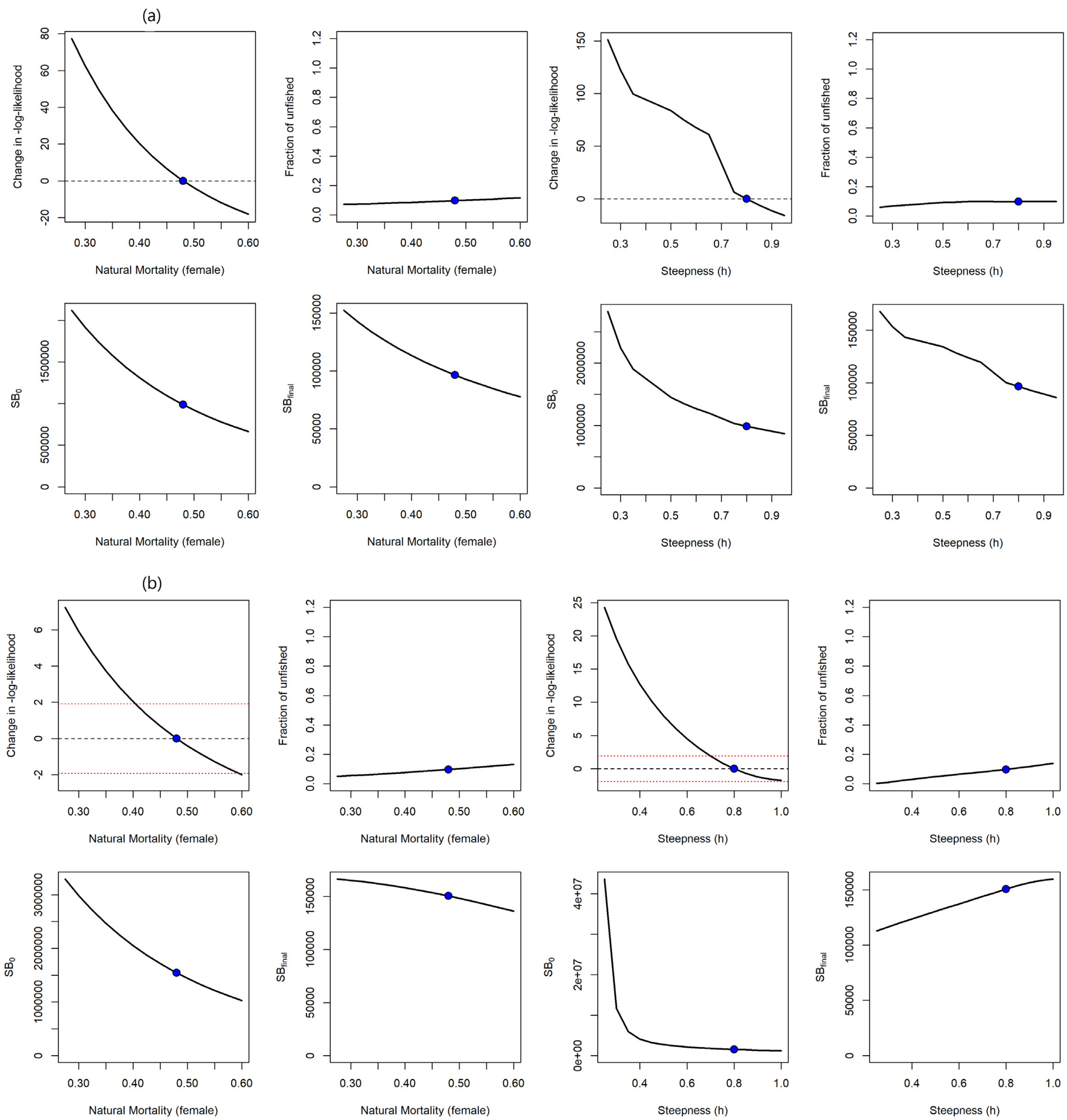

Figure 6. Likelihood profiles for each reference model and parameter. Blue dots represent the reference model value. Plots are (clockwise from top left): likelihood profile (red dotted lines indicated areas of significance around the reference value), relative stock status, unfished spawning output, and spawning output in 2019. (a) No recruitment estimated and (b) recruitment estimated.

tion on larger size classes is an important part of the management strategy.

Highly migratory species like YFT that migrate through several countries' EEZs and into the high seas during their lifetime are notoriously difficult to manage. However, implementing a restriction on the annual catch—a management measure known as total allowable catch (TAC)—has been effective in rebuilding depleted fish stocks as long as catch can be monitored and compliance is high (Melnychuk *et al.*, 2012; Hilborn and Ovando, 2014). Controlling TAC has had an impact on rebuilding bluefin (*Thunnus thynnus*) and billfish (*Istiophoriformes*) biomasses and, to a lesser extent, on reducing the exploitation rates, compared with some input measures (Pons *et al.*, 2017). However, fundamental factors such as limited resources for fisheries management (and thus the absence of routine data collection and monitoring programmes) and the need to maximize food security and employment render the application of TAC extremely difficult for these stocks. Under such circumstances, size restrictions, which are easier to implement, could assist not only in averting overfishing, but also in maintaining the spawning stock output at sustainable levels. For example, by set-

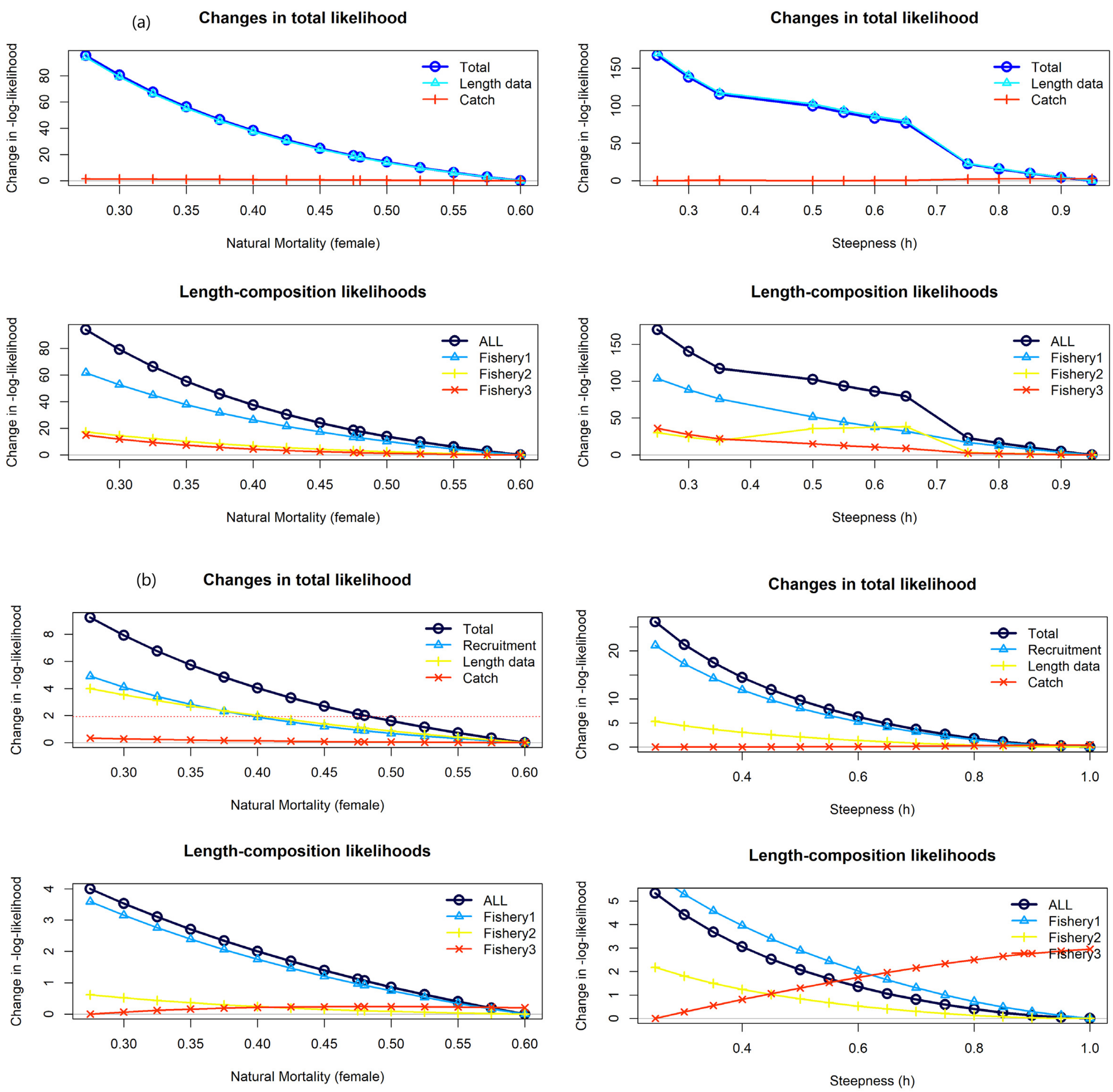

Figure 7. Likelihood profile component plots for each of the reference models and parameters. (a) No recruitment estimated and (b) recruitment estimated.

ting the minimum size at or above the size of maturity, studies have found that fisheries are expected to generate at least 80% of the MSYs while maintaining the biomass at healthy levels, without controlling the exploitation rates (Froese and Binohlan, 2000; Prince and Hordyk, 2019). Given the benefits of well-designed size or gear restrictions, we encourage follow-up fishing trials that explore the effects of size restrictions—through changing the mean length at selectivity—on future biomass and fishery yields of YFT in the Sea of Oman.

The modelling exercise here had limited data to estimate variable recruitment, believed to be a common characteristic of tuna stocks. The two reference models, with and without recruitment variability, were meant to provide some additional dimension of uncertainty, given those two distinct assumptions on the productivity of the stock. While the variable recruitment model does present a more optimistic future if the signal of recent recruitments is correct (though with large uncertainty), both models suggest that intense exploitation over the last 20 years has significantly reduced the YFT stock. Continued biological data collection needs to be a priority in order to follow the signal of recruits in the population and resolve the uncertainty in the forecasted population trend. Any failed recruitments or even average recruitment could continue to destabilize the population, arguing for management measures that protect the immature and recently mature portions of the population to promote future recruitment. Continued data collection can also help resolve the current need to rely on life history values for the literature. In particular, management measures which allow the stock to increase, coupled with representative biological

Table 3. Model output for spawning output relative to unfished spawning output (SO_0) or spawning output at MSY and fishing intensity metrics (1−SPR) for the last two modelled years of the two reference models for yellowfin tuna. Reference points based on MSY estimates are also provided. Comparison between year 2019 and the reference point values are included. For the *SO* comparisons, a value < 1 indicates relative spawning output below the reference point. For the fishing intensity comparison, a value > 1 is higher than the reference point.

Model output	No recruitment estimation	Recruitment estimation
Current measures		
SO_{2019}/SO_0	0.10	0.10
SO_{2020}/SO_0	0.04	0.22
SO_{2019}/SO_{MSY}	0.35	0.35
SO_{2020}/SO_{MSY}	0.14	0.77
$1{-}SPR_{2019}$	0.89	0.78
$1{-}SPR_{2020}$	0.95	0.48
MSY Reference points		
SO_{MSY}/SO_0	0.28	0.28
SO/SO_{MSY}	0.50	0.50
$1{-}SPR_{MSY}$	0.67	0.68
Reference point		
$(SO_{2019}/SO_0)/(SO_{MSY}/SO_0)$	0.35	0.35
$(SO_{2019}/SO_{MSY})/(SO/SO_{MSY})$	0.70	0.70
$(1{-}SPR_{2019})/(1{-}SPR_{MSY})$	1.33	1.16

composition collections (i.e. length compositions) from the fisheries, can provide the contrast needed for the model to improve the information content on parameters like steepness and natural mortality, allowing better understanding on the productivity and absolute size of the population. The poor fits to the longline and purse-seine fisheries may be due to representative sampling issues, thus the collection of data for those fisheries needs to be further evaluated to ensure more population signal in the data. It seems typical for tuna length frequency data to show shifts from year to year in modal length, which can be due to non-random sampling, recruitment variation, or possibly mixing of individuals from other areas of the Indian Ocean. Non-random sampling may be the more likely issue; tuna school by size, and when a boat comes in, it typically has taken most of its catch from a few schools and so will have a hold filled with either small or large fish. Port samplers very often measure large numbers of fish, but from just a few boats, so the data are not representative of the total catch over all boats.

Several recommendations to rebuild the YFT stock in the Sea of Oman result from this study: increasing gillnet mesh size, overall reduction in fishing effort of the gillnet fishery, especially through adjusting the length of the net panel, and gradually replacing a part of the gillnet fleet with longliners that need improved sampling to ensure data representativeness. These changes may provide part of the relief needed to rebuild the tuna stock in the Sea of Oman.

Data availability

All data and results are presented in the manuscript, raw data can be achieved upon request.

Author contributions

ME and JC contributed to the study conception and design. ME, PR, and RAN collected specimens and performed laboratory measurements. Data preparation and analysis was performed by ME, PR, and PB. Statistical analyses were performed by JC. ME and JC wrote the initial draft of the manuscript; and ME was the main driver behind the writing throughout the process. All authors gave comments on previous versions and read and approved the final manuscript.

Statement of competing interests

The authors declare no conflict of interest.

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