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

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Abstract

Over the last decades, views on fisheries management have oscillated between alarm and trust in the management process. The predominant policy for remedying the world fishing crisis aims at maximum sustainable yield (MSY) by adjusting gear selectivity and fishing effort to meet sustainable stock levels. The yellowfin tuna fishery in the Sea of Oman has experienced intense increases in removals since 1980, with particularly high levels since the 1990s. Here we provide an analysis of the fisheries and a preliminary evaluation of stock status for yellowfin tuna in the Sea of Oman since the start of the fishery in 1950 to 2019. Despite limited data, population models indicate a sharp decline in population status since the beginning of the time series, despite a variety of assumptions on stock productivity and life history. The gillnet fishery is almost exclusively taking immature individuals with high fishing intensity and removal rates. Adjusting the interactions of that fishery with the population, while continuing to collection 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: tuna, stock assessment, model uncertainty, data-limited, gear selectivity, spawning output, fisheries management.

1. Introduction

As top predators in the oceans, tuna populations play an important role in pelagic ecosystems and provide worldwide protein requirements (Gilman et al. 2017; McCluney et al. 2019). Large predatory fish such as tunas contributes to the well-being of the numerous fishing communities and food security, particularly in the northern Indian Ocean countries such as Pakistan, Oman, Yemen and Iran, contributing to the reduction of poverty and hunger in the coastal regions of these countries. Yellowfin tuna (*Thunnus albacares*) is one of the most targeted tuna species in the Indian Ocean (Somvanshi, 2002; Zhang et al. 2013) with a volume of landings estimated at 400 000 mt in 2019. In 2017, the catch of the yellowfin tuna in Iran had exceeded the national catch of all the countries targeting yellowfin tuna in the Indian Ocean (IOTC, 2019), with Iran's catch roughly tripled from 19,482 t in 2008 to 56,121 t in 2017. This ever-increasing catch trend is largely driven by the elevated demand for seafood in Iran's domestic market, fueling massive build-up in Iran's tuna fisheries. Yet despite the growing socioeconomic importance of yellowfin tuna in Iran, exploitation rates remain unregulated in artisanal fisheries.

The yellowfin tuna is listed as "near threatened" on the IUCN Red List of Endangered Species (IUCN, 2016). While yellowfin tuna stocks in the Western and Central Pacific are considered to be in good shape and stocks in the Atlantic and Eastern Pacific are doing relatively well, the yellowfin stock in the Indian Ocean are perceived to be overfished and at risk of collapse (IOTC, 2019; Winker et al. 2019). In 2015, this stock was determined to be overfished and subject to overfishing, with 94 percent certainty that this was the case (IOTC, 2015). The following year, another stock assessment returned slightly more optimistic results, with only a 67.6 percent certainty that the stock was both overfished and subject to continued overfishing (IOTC, 2016). IOTC's interim plan required Iran to reduce yellowfin catches by 10 percent, based on 2014 levels (IOTC, 2016; Resolution 16/01) corresponding to a threshold of 30 000 mt. While the yellowfin stock in the Indian Ocean basin is considered as unique, the status of the part of the stock exploited in Iran's exclusive economic zones is unknown, the build-up of fishing fleets to expand the production combined with high market demand raises concerns about the sustainability of the stock. Left unnoticed, overfishing would reduce catch, impact food security and the livelihoods of the fishing communities in Iran, especially given yellowfin tuna is predominantly fished by the artisanal sector (Kaymaram et al. 2014; IOTC, 2018).

In this study, we describe fisheries targeting the yellowfin tuna in Iran's EEZ of the Sea of Oman and examine their catch compositions harvested in four fishing grounds – representing the main fishing grounds of yellowfin tuna in Sea of Oman. We apply a statistical catch-at-age model to the time series of catches and limited length composition data to obtain a preliminary and general understanding of the population dynamics of this stock consistent with the life history and limited fishery-dependent data. Our study may aid in steering management efforts in Iran toward the sustainability of the yellowfin stock in the whole Indian Ocean.

2. Yellowfin tuna catch trend

The yellowfin tuna (YFT) catch in the Iran's EEZ increased gradually to about 20 000 mt in the early 1990s, and thereafter rapidly to 40 000 to 50 000 mt by 2000s. The rapid increase is mostly due to the introduction of more fishing vessels in the early 1990s mainly targeting YFT.

Due to the high market demand in Iran, YFT is harvested by different fishing gears. It has a major commercial importance to the income of the local fishermen and the supply chain involved (Hosseini and Kaymaram, 2015). Compared with others fishing regions of the Indian Ocean, the gillnet in the Sea of Oman contributes to the catch much more significantly. On average, over the period ranged from 1950 to 2018, gillnets are responsible for around 75 % of YFT the catches, followed by purse seine fisheries at 10 % (Fig.1).

In Iran the gillnet fishery has always been the major fishery. The longline catch then started increasing due to the increase in the number of artisanal longline fishing vessels and reached almost 12 000 mt by 2018. However, the development of the purse-seine fishery started in 1992, and its catches had even reached to 11 000 mt in 2004. Hook and line catches have increased gradually since 2005, and reached a maximum of about 700 mt in 2018, but is still scarce.

2.1 Description of fisheries targeting yellowfin tuna

Gillnet

Surface-set gillnet operated in Hormuzgan and Sistan-Baluchestan provinces throughout the year with the stretched mesh size ranging from 100mm to 120mm twine material made entirely from conventional polyamide multifilament (manufacturer's specifications of 210D/36). The length of net panels ranged between 8 and 10 km. Active artisanal gillnetters are around 3160 vessels. However, artisanal gillnet vessels decreased in recent years and replaced by the longline fishery. The artisanal gillnetting has been used in fiberglass boats and dhows. The boats used are varied with the overall length of 5.5 to 7m equipped with petrol engines of 48 to 55 hp with a crew of about 5 fishermen doing short cruises of 3 days on average. The overall length for dhows ranged from 18 to 32m, which are operated by diesel engines of 240 to 850 hp. The crew on dhows represents 15 fishermen on average staying 30 days at sea. Gillnet fishery performed throughout the year in both nearshore (mainly fiberglass boats) and offshore (mainly dhows) waters of Iran. Gillnet is the most common fishing gear used in Iran, where approximately more than 93% of the fish are caught using gillnet, including YFT. Gillnets selectivity is presumed to be dome-shaped, as it generally includes fish <100cm.

Longline

The longline fishery targeting YFT in Iran EEZ was initiated in 1995 with an industrial Taiwanese style longliner owned by an Iranian company. The artisanal pelagic longline fishery practically started about four years ago and gradually expanded with steady gillnet decline. The fishing gear consisted of a standard monofilament polyamide mainline of 3mm diameter (~25 km long; stored on a drum), with four branchlines between floats. Branchlines are connected with the main line by a snap clip. A swivel is used to connect the branchline to the snap clip to avoid twist. The max depth of the mainline at the center of a basket was 78m. Common bait types are live sardine and Indian mackerel in size of 25 to

30cm. The common hook type is circle hook in sizes ranging from 11/0 to 14/0. Active artisanal longliners are about 950 dhows and 1350 boats, with 20 thousand fishermen involved in this fishery mostly in Sistan-Baluchestan province. The artisanal longlining has been used in a small number of fiberglass boats and dhows. As for the gillnet fleet the fiberglass boats used are varied for the overall length of 5.5 to 7m equipped with petrol engines of 48 to 55 hp doing daily cruises with 4 fishermen on board. The overall length for dhows ranged from 18 to 32m, which are operated by diesel engines of 240 to 850 hp with 12 fishermen on board staying 7 days at sea on average. Artisanal longline fishery is active during the year both in nearshore (mainly fiberglass boats) and offshore (dhows) waters of Iran. Longline fishery selectivity is presumed logistic (i.e., S-shaped) as this fishery may include the biggest fish available.

Purse seine

Purse seine operations started in 1992 in Iran. The tuna purse seine fishery is the only industrial fishery in the Iranian waters of Oman Sea. Iranian purse seiners have a length overall around 99.5 m and are equipped with a Global Positioning System (GPS), sonar, echo sounder and a purse seine net and the skiff boat. The purse seine net has a floating line about 1886m long and a lead line of 2026m. The maximum altitude of the net (stretched net depth) is 210m and stretched mesh size varying between 16 and 18cm. A purse seine is operated only in offshore waters to target in general tuna aggregations around the fish aggregative devices (FADs). Currently, five purse seiners targeting YFT operated 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 of 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 fishermen 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 into the level of the sea where tuna are found abundant. Fishermen generally use natural baits such as squid, 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 reel. Tuna HL fishing is a seasonal practice and carried out only in coastal waters of Sistan-Baluchestan province. Currently, 1645 HL fishing vessels targeting yellowfin tuna operated in the coastal waters of Iran. The catch harvested by this fishery was minimal and not included in the model.

3. Methods

3.1 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 not included in the population modelling. Length frequency data of the yellowfin tuna were collected at the four sampling localities consist of one landing site in Hormuzgan Province, two landing sites in Sistan-Baluchestan Province and one in offshore waters in the alongside the Persian Gulf and Oman sea coastlines (Fig. 2). Georeferenced data on catch are not available but from interview with fishermen we are able to roughly localised the fishing grounds related 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 distributed from January 2015 to December 2019. Catch data were collected in all the above landing centers by stratified random sampling by the port samplers, in this way, total fishing crafts for different vessel classes of fishing dhows and boats were picked out randomly. Length-based metrics to provide information on the length of the catch (fork length) nearest to ½ cm and its range were calculated for each gear.

3.2 Estimating population dynamics and stock trajectory

The integrative statistical catch-at-age modelling framework Stock Synthesis (SS v.3.30.16; Methot and Wetzel, 2013) was used to estimate stock trajectory given the inputted data and fixed and estimated model parameters. The SS-DL tool (https://github.com/shcaba/SS-DL-tool) was used to conduct all analyses and produce plots using the r4ss package (https://github.com/r4ss/r4ss).

The model was assumed as one sex and one area, thus no movement in an out of the assessed model. 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 lengths samples, and all other years relative to 200 by the ratio of yearly sample: maximum sample. The Dirichlet-multinomial was used to weight the length compositions in the model (Thorson et al. 2017).

All life history values were fixed (Table 1), with the only estimated parameters being the natural logarithm of the initial recruitment size (lnR_0) and the selectivity parameters, with recruitment estimated in one reference scenario. A 6-parameter double-normal specification for selectivity was used (SS selectivity option 24), with 5 parameters being estimated for the dome-shaped gillnet fishery (1 fixed), and two parameters being estimated for the longline and purse seine logistic fleets (the other 4 fixed parameters ensure logistic behavior on the descending limb of the function). Two reference models were explored based on whether recruitment was or was not estimated for the whole 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.

3.3 Uncertainty

Uncertainty was expressed in two main ways. 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 parameters at 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. Likelihood profiles for natural mortality and recruitment compensation (steepness) were explored. 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.

3.4 Fisheries reference points

Defining reference points are critical in 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 report estimated values for maximum sustainable yield (MSY and 1-SPR_{MSY}) for context.

4. Results

A total of 170082 yellowfin 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 to December 2019).

4.1 Yellowfin Tuna fisheries

The most widespread fishery targeting tuna in the Indian Ocean is the gillnet fishery. In 2015 to 2019, the gillnet fishery targeted yellowfin tuna in all the sampled locations. This large spatial distribution of the gillnet fishery facilitates greater access to the tuna resource than any others, which may explain why the catch of the gillnet fishery represents about 90% of the total YFT catch for all fishing gears over the past decade (Fig. 1). Along with the gillnet fishery, the fishing grounds of hook and line and longline fisheries overlap in 2 and 3 during 2015 to 2019. On the contrary, the fishing ground of the purse seine fishery does not overlap with any other fishery, which targets the yellowfin tuna in offshore waters in over the years.

4.2 Length Composition

The highest mean length of the yellowfin tuna 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). Contrary to the gillnet fishery, the length samples obtained from the other fisheries yielded a much higher mean length (>100 cm) than that obtained from gillnet fishery. Larger individuals of yellowfin tuna were caught significantly more by longline ($P<0.05$). The range of the length classes of the yellowfin tuna 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 in five sampling years (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 longlines and hook and lines contained very small fractions of immature fish (6% and 3%, respectively).

4.3. Model diagnostics

Both reference models were able to invert the Hessian, and thus estimate variances on parameters and derived outputs. This and reasonably low gradient values were indicative of converged models. These models were based on the best fit model from 100 model runs with jittered starting values of estimated parameters to ensure local minima were avoided.

Fits to the limited length data were adequate, with the best overall fits to the gillnet fishery (Figure 3). The gillnet and purse seine fisheries showed less prominent fits to the data, indicating some level of model misspecification that could not be captured in either recruitment or time-invariant selectivity estimation. 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).

4.4 Population dynamics and stock status interpretation

Exploitation rates have increased steadily over the 1990-2018 period (Figure 1). The stock dynamics have shown a strong response to this increase is exploitation rates with a demonstrative decline in spawning output over time regardless of the estimation of recruitment (Figure 5). Both reference models indicate the population is essentially at the same relative stock status (10% of unfished; Table 3) but 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 only provides recruitment information for the most recent years (Figure 5), with several high recruitments in the last 5 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 the current stock status is very low. It is only under the assumption of large recent recruitments the population can show the potential for recovery.

4.4 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 the 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 either massive model misspecification (unlikely the situation in this case) or limited information in the data to inform the parameter. 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 (Fishery1, Figure 7), as it is the best fit data set, but dome-shaped fisheries are notoriously confounded with natural mortality. Despite the large range of values explored for both natural mortality and steepness, the relative stock size never gets above 20% in 2019 even in the most biologically productive scenarios (Figure 6).

4.5 Fisheries reference points

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 (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 high probability the current status of yellowfin tuna is below this value.

5. Discussion

Though the socioeconomic importance of yellowfin tuna is growing in Iran – currently the largest harvesting and largest amount of yellowfin tuna 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 gillnet fishery is, by far, provide the largest proportion (75%) of yellowfin tuna catch in Iran. Further, the current spawning output is below the MSY and MSY-proxy fisheries reference points, while the fishing intensity is above those references.

The historical yellowfin tuna trajectory shown in this study is consistent with that estimated by earlier reports that predicted that biomass and exploitation rates were unsustainable (Lee et al., 2013; Langley, 2015; Urtizberea et al., 2019), and the most recent report is showing that the stock is overfished and experience excessive exploitation rates in the Indian Ocean (IOTC 2018; Winker et al. 2019). The current stock size is likely severely depleted (estimated depletion in 2019 < 20%), the high exploitation rates continue to threaten the sustainability of the stock. The lack of fisheries regulations is equally alarming, particularly that the market demand for yellowfin tuna is unlikely to diminish in the near future. Indian Ocean yellowfin is currently raise difficulties to find a management strategy aiming to reach a sustainable biomass even at mid-term, by the industry's own admission. Scientists recommended in 2015 that a 20 percent reduction in catches was necessary to give the stock a 50 percent chance of recovery by 2024 (IOTC, 2018b).

Based on results, larger individuals of yellowfin tuna were caught significantly more by longline, whereas the gillnet fishery targeted individuals almost exclusively below the size at maturity. 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, the largest fraction of immature fish was caught by the gillnet fishery (52.5%), a fishery with one of the highest exploitation rates among the modelled fleets, and catches that continue to increase. This indicated that subjecting the stock to high exploitation rates (estimated from the model) while retaining small and immature fish has shown to result in recruitment overfishing, where recruitment is expected to fall linearly as biomass declines (Walters and Maguire, 1996). Therefore the exploitation pattern should be more selective forwards avoiding 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 on MSY-based approaches, in particular when increased selection on larger size classes is an important part of the management strategy.

Highly migratory species like yellowfin tuna 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). Considering tuna and billfish stocks, TAC has shown the greatest impact on rebuilding bluefin and billfish 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 a limited capacity for fisheries management (and thus the absence of routine data collection and monitoring programs) 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 setting the minimum size at or above the size of maturity, studies have found that fisheries are expected to generate at least 80% of the maximum sustainable yields 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 restrictions, we encourage follow-up fishing trial that explores the effects of size restrictions – through changing the mean length at selectivity – on future biomass and fishery yields of the yellowfin tuna 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 if correct (though with large uncertainty), both model suggest intense exploitation over the last 20 years have significantly reduced the yellowfin tuna 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 that allow the stock to increase coupled with representative biological 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 issue, thus the collection of data for those fisheries need 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 either to non-random sampling or to recruitment variation. Likely non-random sampling is the more common problem: 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 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 at all of the total catch over all boats.

Several recommendations to rebuild the yellowfin tuna stock in the Sea of Oman result from this study. It may generally be suggested to modify gillnets mesh size, reduces the fishing effort of gillnet fishery especially through the length of the net panel, and gradually replacing a part of the gillnet fleet by longliners.

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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
Metabolic rate	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
Length at maturity (50%)	L_{50}%	85.5 cm	Kaymaram et al. 2014; Nootmorn et al. 2005; Zhu et al. 2008; Froese, and Pauly, 2019
		100 cm	IOTC, 2017

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

	$\bar{x}$ (cm)	SD (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

Table 3. Model output for spawning output relative to unfished spawning ouput (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.

	Reference model	
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
$1\text{-}SPR_{2019}$	0.89	0.78
$1\text{-}SPR_{2020}$	0.95	0.48
MSY Reference points		
SO_{MSY}/SO_0	0.28	0.28
SO/SO_{MSY}	0.50	0.50
$1\text{-}SPR_{MSY}$	0.67	0.68
2019: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
$(1\text{-}SPR_{2019})/(1\text{-}SPR_{MSY})$	1.33	1.16

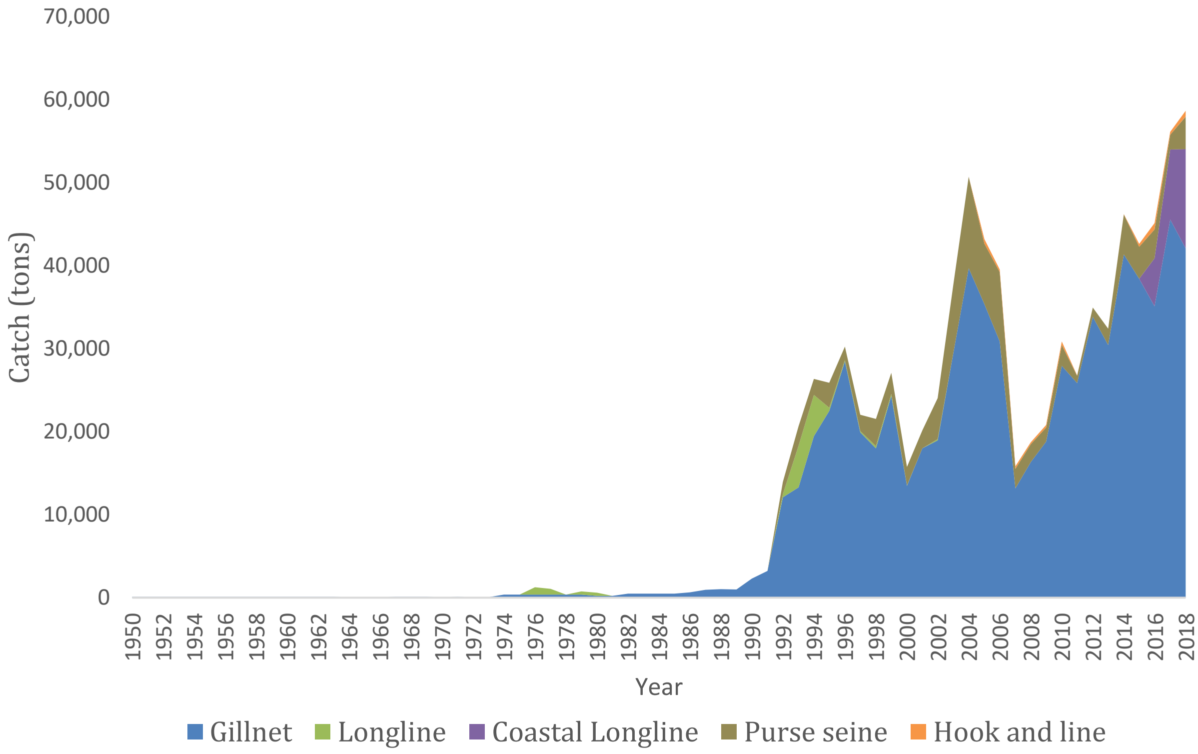


Figure 1. Catch trend of yellowfin tuna harvested by Iranian fleet by each gear (source: Iranian Fisheries Organization).

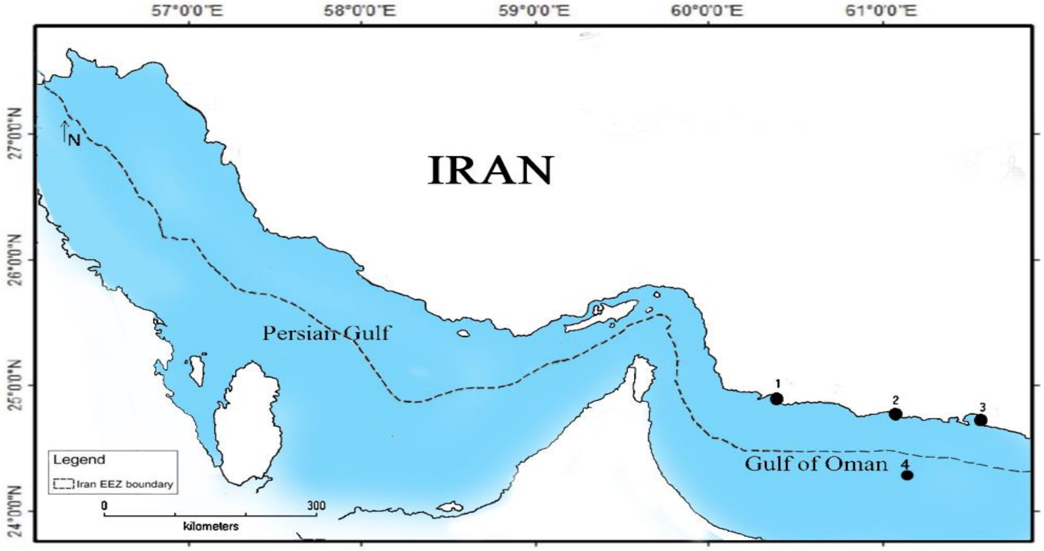
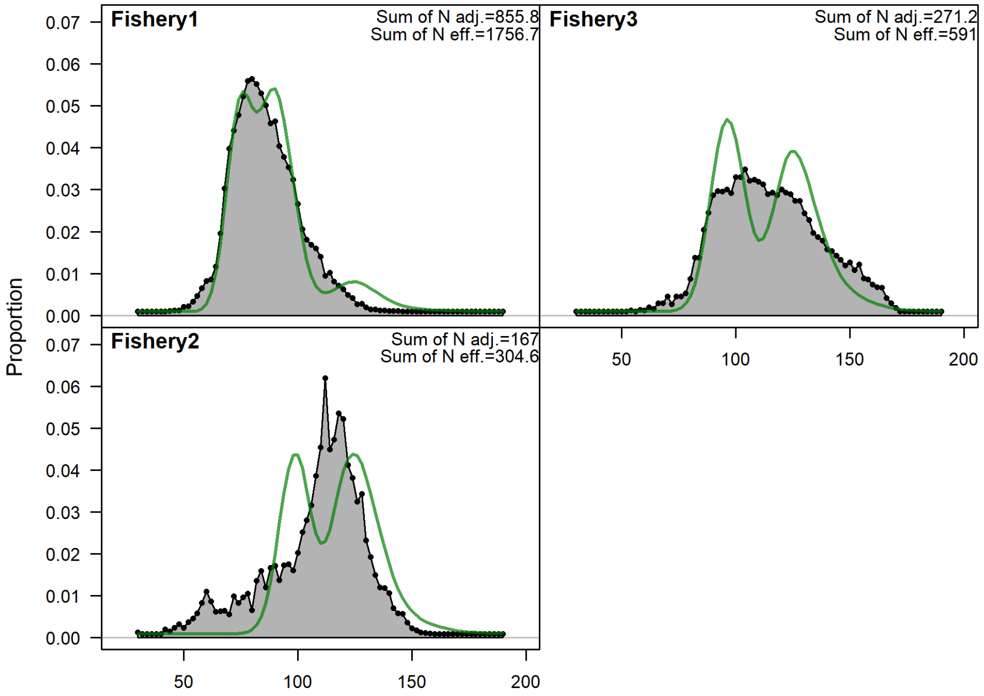


Figure 2. Sampling fishing ports for the present study in the southern coastline of Iran. The filled circles indicate the sampling sites: 1, Jask; (Hormuzgan province); 2, Konarak; 3, Beris and Pasabandar; (Sistan-Baluchestan province); 4, Offshore waters.

A) No recruitment estimation



B) Recruitment estimated

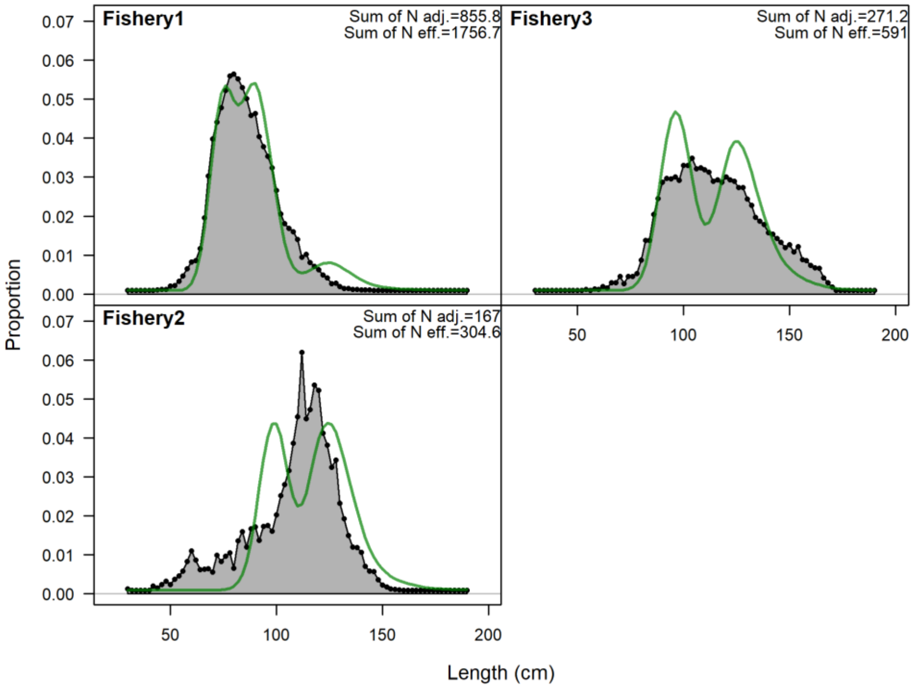
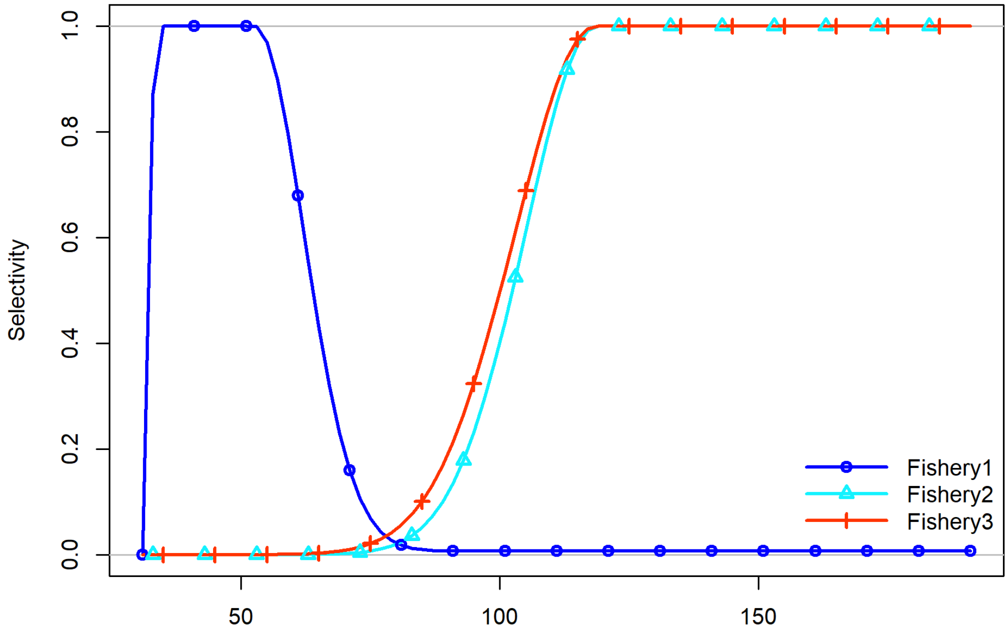


Figure 3. Composite length composition fits to the gillnet (Fishery1), longline (Fishery2) and purse seine (Fishery3) data for each reference model.

A) No recruitment estimation



B) Recruitment estimated

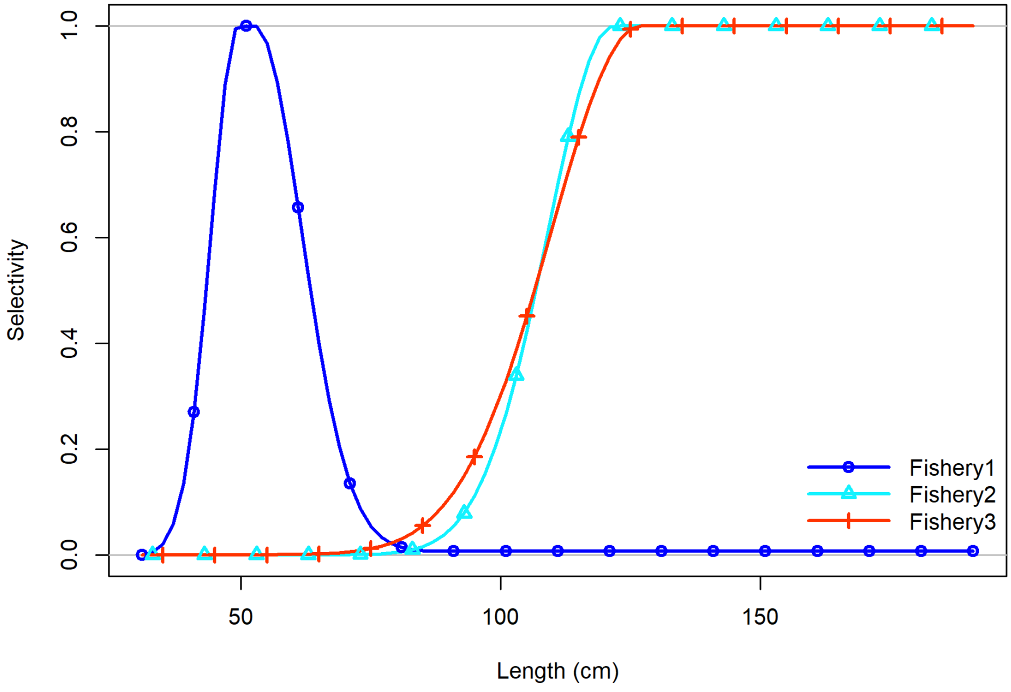


Figure 4. Selectivity estimates for the gillnet (Fishery1), longline (Fishery2) and purse seine (Fishery3) fisheries for each reference model.

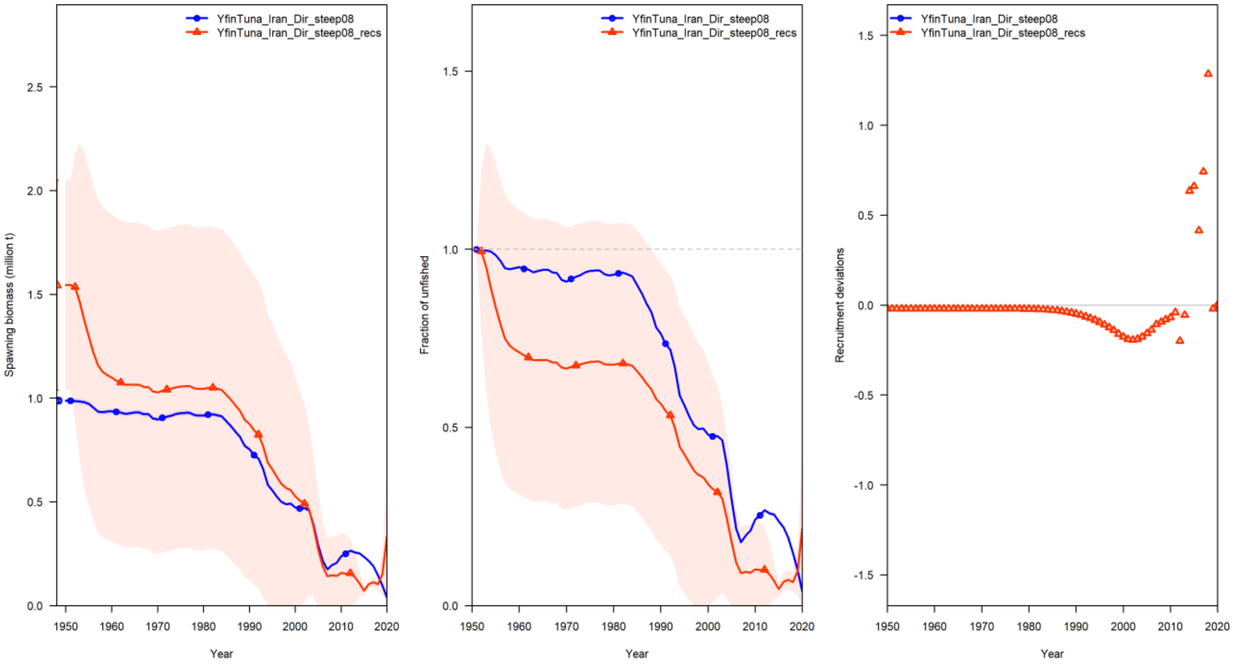
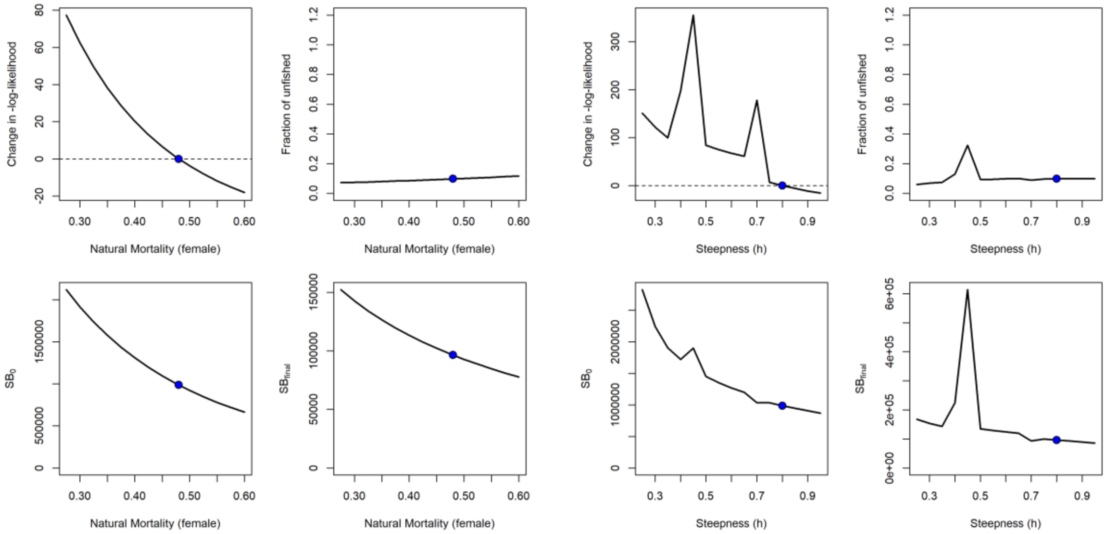


Figure 5. Comparison plots for (left to right) spawning output, relative spawning output and recruitment deviations for yellowfin tuna off Iran. Blue with circles: No recruitment estimation. Red with triangles: recruitment estimation.

A) No recruitment estimation



B) Recruitment estimated

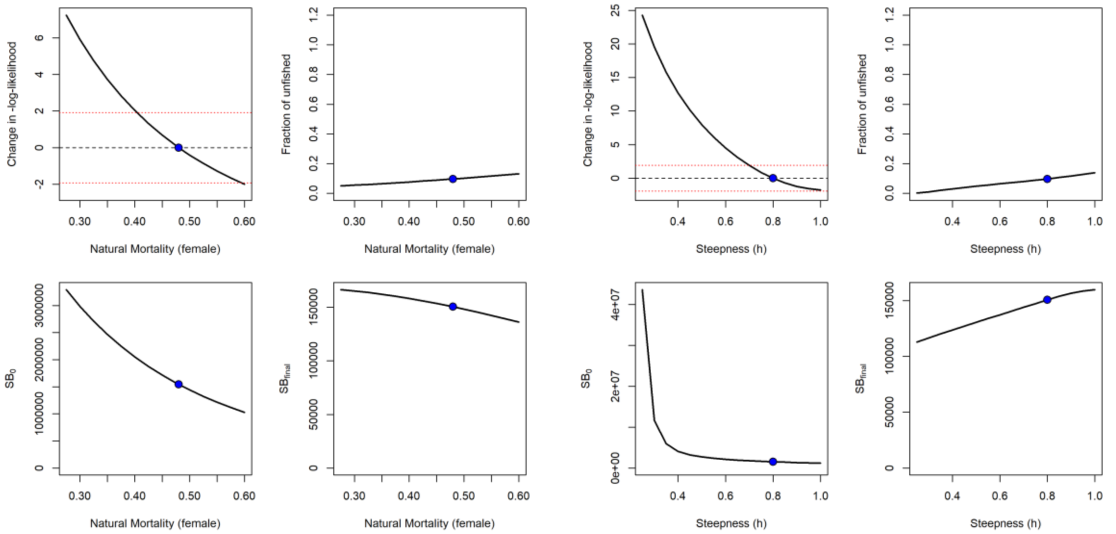
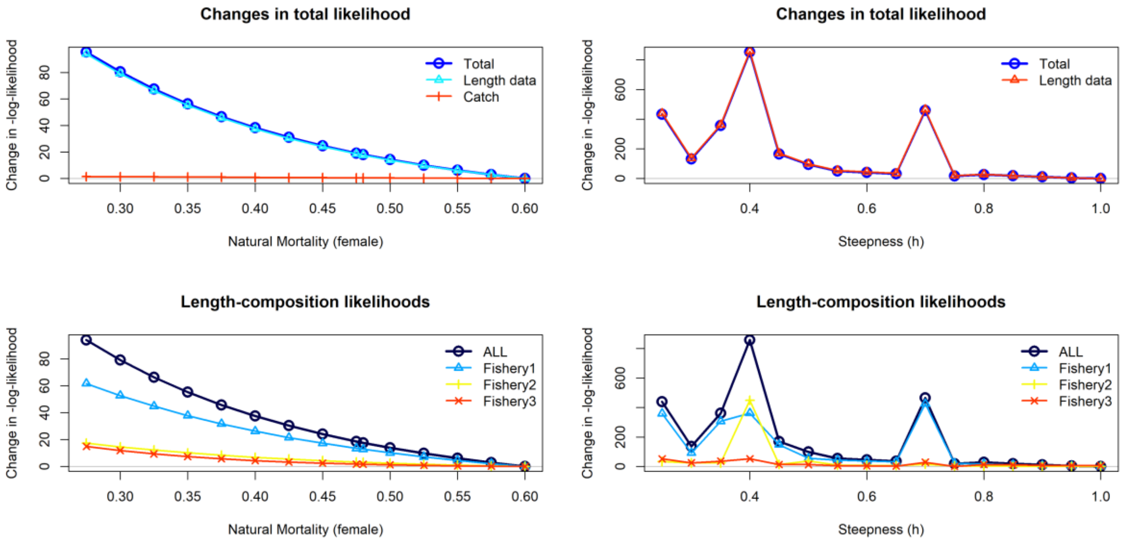


Figure 6. Likelihood profiles for each reference model and parameter. Blue dots representing the reference model value. Plots are (clockwise from top left): Likelihood profile (red dotted lines indicated areas of significance around the reference value), relative stock status, unfished spawning output and spawning output in 2019.

A) No recruitment estimation



B) Recruitment estimated

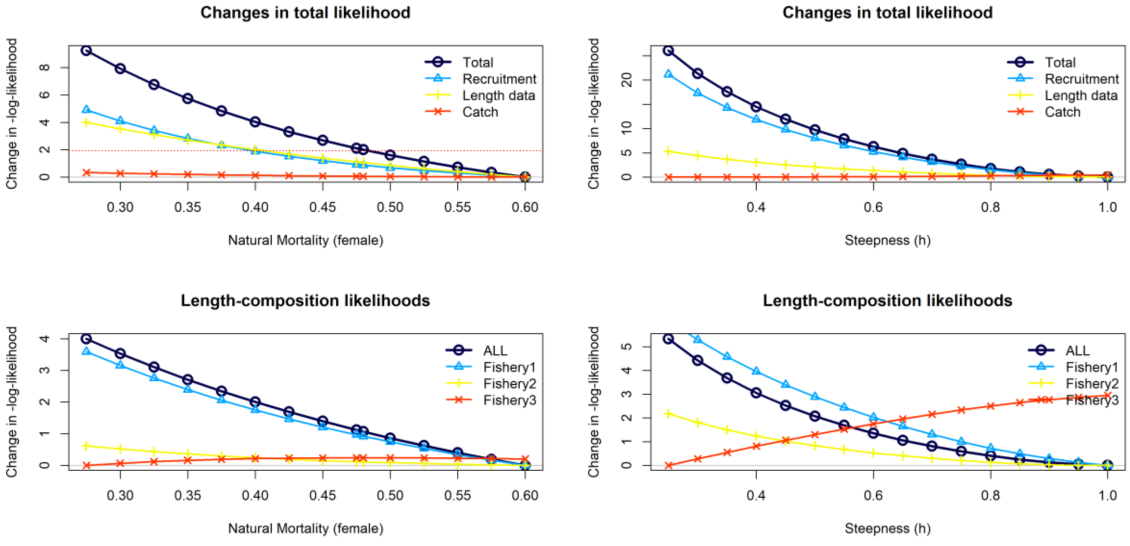


Figure 7. Likelihood profile component plots for each of the reference models and parameters.