Preliminary 2024 stock assessment of yellowfin tuna in the Indian Ocean

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Contents

Executive Summary 3

1 Introduction 4

2 Background 5
2.1 Biology 5
2.2 Stock structure 5
2.3 Fisheries 6

3 Model structure 7
3.1 Spatial stratification 7
3.2 Temporal stratification 8

4 Model inputs 8
4.1 Temporal aggregation 9
4.2 Spatial aggregation 9
4.2.1 Simple aggregation 9
4.2.2 Catch-raised aggregation 9
4.3 Definition of fisheries 10
4.4 Catch 11
4.5 Indices 11
4.5.1 Longline CPUE 11
4.5.2 Purse seine CPUE indices 13
4.5.3 Effort creep 13
4.6 Size data 14
4.7 Age data 14
4.8 Tagging 14

5 Model parameters 14
5.1 Population dynamics 14
5.2 Fishery dynamics 15

5.3 Tagged fish 15
5.4 Likelihood components 15
5.5 Parameter estimation and uncertainty 15
5.6 Stock status 15

6 Model runs **15**
6.1 Update from the last assessment 15
6.2 Sensitivity and structural uncertainty 15

7 Results **15**
7.1 Fits 15
7.2 Parameter estimates 15
7.3 Time series 16
7.4 Sensitivity 16

8 Discussion and conclusions **16**

9 Acknowledgements **16**

10 Tables **17**

11 Figures **20**

12 Appendix **23**
12.1 Acronyms and Abbreviations 23
12.2 Likelihood profiles 23
12.3 Retrospective analyses 23

References **34**

Executive Summary

This report presents a preliminary stock assessment for Indian Ocean yellowfin tuna (*Thunnus albacares*) using Stock Synthesis 3 (SS3). The assessment uses an age-structured and spatially-explicit population model and is fitted to catch rate indices, length-composition data, and tagging data. The assessment covers 1950 – 2023 and represents an update of the previous assessment model, taking into account progress and improvements made since the previous assessment. The assessment assumes that the Indian Ocean yellowfin tuna constitute a single spawning stock, modelled as spatially disaggregated four regions, with 21 fisheries. Standardized CPUE series from the main longline fleets 1975 – 2020 were included in the models as the relative abundance index of exploitable biomass in each region. The CPUE indices from EU Purse seine sets on free schools were included in a subset of models with the spatial and fleet structure revised to better accommodate the distribution and size structure of the purse seine fisheries. Indices based on associative and non-associative dynamics of yellowfin tuna with floating objects were also available, and the utility of these indices was examined in the assessment. Tag release and recovery data from the RTTP-IO program were included in the model to inform abundance, movement, and mortality rates.

1 Introduction

Prior to 2008, Indian Ocean (IO) yellowfin tuna (*Thunnus albacares*) was assessed using methods such as Virtual Population Analysis (VPA) and production models (Nishida and Shono 2007, 2005). In 2008, a preliminary stock assessment of IO yellowfin tuna was conducted using MULTIFAN-CL (Langley et al. 2008) enabling the integration of the tag release/recovery data collected from the large-scale tagging programme conducted in the IO in the preceding years. The MULTIFAN-CL assessment was revised and updated in the following years (Langley et al. 2009; Langley, Herrera, and Million 2010, 2011, 2012).

In 2015, the assessment of IO yellowfin tuna was implemented (Langley 2015), which used the Stock Synthesis 3 modelling platform (Methot and Wetzel 2013). SS3 is conceptually very similar to MFCL and the two platforms have yielded similar results. On basis of that assessment, the yellowfin tuna stock was determined to be overfished and subject to overfishing. At its 20th meeting, the Indian Ocean Tuna Commission (IOTC) adopted an Interim Plan for Rebuilding the Indian Ocean Yellowfin Tuna Stock (Res. 16/01).

The SS3 assessment was updated in 2016 (Langley 2016) and was revised and updated in 2018 (Fu et al. 2018). These assessments utilised new composite longline CPUE indices derived from the main distant water longline fleets, replacing the Japanese longline CPUE indices used previously. The 2018 assessment also included a comprehensive analysis of the main assumptions of the stock assessment. A model ensemble covering major components of structural uncertainty was used to characterise the stock status. The assessment estimated that the spawning stock biomass in 2017 was below SSB_{MSY}, and that fishing mortality was above F_{MSY}. Therefore, the stock status was determined to remain overfished and experiencing overfishing.

An external review of the 2018 assessment provided recommendations to improve model parametrisations (Methot 2019). An attempt was made to update the assessment in 2019, with extensive investigations of alternative spatial structures, data weighting and biological parameters (Urtizberea et al. 2019). Further analysis was conducted in 2020 to refine the process of model selection through an objective scoring system based on diagnostic metrics (Urtizberea et al. 2020).

The most recent assessment was conducted in 2021 (Fu et al. 2021), which also used SS3 as the modelling platform and was based on the four area spatial configuration as in 2018. This recent assessment included an standardised CPUE series from the main longline fleets as the main index, but also tested the inclusion of EU purse seine indices, operating on free schools and floating objects, and an index from the Maldivian pole and line fishery. A range of exploratory models were presented to address issues in observational datasets, improve the stability of the assessment model, and explore the effects of alternative model assumptions. Overall stock status estimates do not differ substantially from the 2018 assessment, estimating $SSB/SSB_{MSY} = 0.78$ and $F/F_{MSY} = 1.27$ for the last model year, which suggest that the stock is overfished and experiencing overfishing.

An external review of the 2021 assessment was carried out in 2023 (Maunder et al. 2023), and provided a set of recommendations for the next assessment implementation. This report documents the next iteration of the stock assessment of the IO yellowfin tuna stock for consideration at the 26th WPTT meeting. This stock assessment includes fishery and biological data up to the end of 2023 and its configuration is based on the 2021 assessment. It implements an age- and spatially-structured population model using SS3 (v3.30.22.1) and incorporates some revisions made by the last external review.

2 Background

2.1 Biology

Yellowfin tuna is a cosmopolitan species distributed mainly in the tropical and subtropical oceanic waters of the three major oceans, where it forms large schools. Spawning occurs mainly from December to March in lower latitudes with warmer waters and mesoscale oceanographic activity (Muhling et al. 2017), with the main spawning grounds west of 75°E. However, spawning activity has also been reported in the Oman Sea (Hosseini and Kaymaram 2016), Bay of Bengal (Kumar and Ghosh 2022), off Sri Lanka and the Mozambique Channel, and in the eastern IO off Australia Nootmorn, Yakoh, and Kawises (2005). The size at 50% maturity for this species in the IO was initially estimated at around 75 cm based on cortical alveolar stage (Zudaire et al. 2013), but an updated study suggests that it might be at a larger size ($\sim$ 101 cm) (Zudaire et al. 2022). Tag recoveries provide evidence of large movements of yellowfin tuna within the western equatorial region; however, few observations of large-scale transverse movements in the IO have been reported (Gaertner and Hallier 2015). Yellowfin dwell preferentially in the surface mixed layer and the thermocline (Pecoraro et al. 2017), above 200 m approximately (Sabarros, Romanov, and Bach 2015).

This species has a high metabolic rate and, therefore, it requires large energy supplies to fulfill the bioenergetics demands for movement, growth, and reproduction (Artetxe-Arrate et al. 2021). Feeding behaviour is largely opportunistic, with a variety of prey species being consumed, including large concentrations of crustacean that have occurred recently in the tropical areas and small mesopelagic fishes (Krishnan et al. 2024; Roger 1994; Duffy et al. 2017). Recent growth studies have generally supported a two-stanza growth curve, with a slow initial growth phase up to $\sim$ 60 cm followed by much faster growth (Farley et al. 2023). In addition, differences in mean length-at-age have been identified between males and females for fish older than four years. Environmental variability in the IO impacts the abundance and catch rates of this species. A significant negative association between the Indian Ocean Dipoles (IODs) and the catch rates of yellowfin tuna with a periodicity of approximately four years was observed (Lan, Evans, and Lee 2013; Lan, Chang, and Wu 2020). Likewise, Lan, Chang, and Wu (2020) also found that the El Niño Southern Oscillation (ENSO) had an impact on catch rates near the Arabian Sea.

2.2 Stock structure

Fisheries information indicates that adult yellowfin are distributed continuously throughout the entire tropical Indian Ocean, but some more detailed analysis of fisheries data suggests that the stock structure may be more complex. The tag recoveries may indicate that the western and eastern regions of the IO support relatively discrete sub-populations of yellowfin tuna. Studies of stock structure using DNA techniques have indicated that there may be genetically discrete sub-populations of yellowfin tuna in the northwestern IO (Dammannagoda, Hurwood, and Mather 2008) and within Indian waters (Kunal et al. 2013). A recent study of stock structure using the gene sequencing technology along with a basin-scale sampling design indicated genetic differentiation between north and south of the equator within the IO, and possibly additional genetic structure within the locations north of the equator (Grewe et al. 2020). Parasite composition and abundance suggest limited movement of yellowfin between Indonesian archipelago (eastern IO) and the Maldives (central IO) (Moore et al. 2019). Isotope studies have also suggested relatively limited movement, with resident behaviour at the temporal scale of their muscle turnover

(∼ 3 months) (Ménard et al. 2007). Otolith chemistry analyses concluded that fisheries operating in the western IO are mainly composed of fish with western origin, which suggest limited movement from east to west (Artetxe-Arrate et al. in review). These studies generally support the potential presence of population units of yellowfin tuna within the IO, despite that considerable uncertainty remains on sub-regional population structure in this region. This assessment assumes that the IO yellowfin tuna stock consists of several interconnected regional populations Figure 1 that have the same biological characteristics; however, we acknowledge that more studies are needed to reveal the structure of this species.

2.3 Fisheries

Yellowfin tuna are harvested with a diverse variety of gear types, from small-scale artisanal fisheries (in the Arabian Sea, Mozambique Channel and waters around Indonesia, Sri Lanka, the Maldives, and Lakshadweep Islands) to large gillnetters (from Oman, Iran and Pakistan operating mostly but not exclusively in the Arabian Sea) and distant-water longliners and purse seiners that operate widely in equatorial and tropical waters (Figure 5). Purse seiners and gillnetters catch a wide size range of yellowfin tuna, whereas the longline fishery takes mostly adult fish (Figure 4).

Prior to 1980, annual catches of yellowfin tuna remained below about 80,000 mt and were dominated by longline catches (Figure 2). Annual catches increased markedly during the 1980s and early 1990s, mainly due to the development of the purse-seine fishery as well as an expansion of the other established fisheries (fresh-tuna longline, gillnet, baitboat, handline and, to a lesser extent, troll). A peak in catches was recorded in 1993, with catches over 400,000 mt, the increase in catch almost fully attributable to longline fleets, particularly longliners flagged in Taiwan, which reported exceptional catches of yellowfin tuna in the Arabian Sea. The Taiwanese longline fishery in the IO has been equipped with super-cold storage. Since around 1986, the fleet has fished more frequently with deep sets.

Catches declined in 1994, to about 350,000 mt, remaining at that level for the next decade then increasing sharply to reach a peak of about 520,000 mt in 2004-2005 driven by a large increase in catch by all fisheries, especially the purse-seine (free school) fishery. Total annual catches declined sharply from 2004 to 2007 and remained at about 300,000 mt during 2007–2011. In 2012, total catches increased to about 400,000 mt and were maintained at about that level through 2013 to 2015. Total catches increased to an average of 430,000 mt between 2016 and 2019, and a maximum of close to 450,000 mt in 2019 (Figure 2), despite IOTC Resolution 17/01 which requested major fleets to substantially reduce their yellowfin catches below the 2014 or 2015 catch level. Furthermore, catch levels of about 440,000 mt reported for 2018 might be under-estimated (to some extent) because of changes in data processing methodology by European Union-Spain for its purse seine fleet for that year (IOTC 2021).

In recent years (2015–2023), purse seine has been the dominant fishing method harvesting 36% of the total IO yellowfin tuna catch (by weight), with the gillnet and handline fisheries, comprising 20% and 18% of the catch, respectively. There was a substantial increase in the catch by handline in 2020 (Figure 2). A smaller component of the catch was taken by industrial longline (5%), and the regionally important baitboat (4%) and troll (4%) fisheries. The recent increase in the total catch has been mostly attributable to an increase in catch from the gillnet and handline fisheries.

The purse-seine catch is generally distributed equally between free-school and associated (log and FAD sets) schools, although the large catches in 2003–2005 were dominated by fishing on free-schools. Conversely, during 2015–2023 the purse-seine catch was dominated (70%) by the associated fishery.

Historically, most of the yellowfin catch has been taken from the western equatorial region of the IO (44%; region 1b, Figure 5) and, to a lesser extent, the Arabian Sea (26%), the eastern equatorial region (24%, region 4) and the Mozambique Channel (5%; region 2). The purse-seine and baitboat fisheries operate almost exclusively within the western equatorial region, while catches from the Arabian Sea are principally by handline, gillnet, and longline (see Figure 5). Catches from the eastern equatorial region (region 4) were dominated by longline and gillnet (around Sri Lanka and Indonesia). The southern IO (region 3) accounts for a small proportion of the total yellowfin catch (1%) taken exclusively by longline.

In recent years (2008–2012), due to the threat of piracy, the bulk of the industrial purse seine and longline fleets moved out of the western waters of Region 1b to avoid the coastal and off-shore waters off Somalia, Kenya and Tanzania. The threat of piracy particularly affected the freezer longline fleet and levels of effort and catch decreased markedly from 2007. The total catch by freezing longliners declined to about 2,000 mt in 2010, a 10-fold decrease in catch from the years before the onset of piracy. Purse seine catches also dropped in 2007–2009 and then started to recover. Piracy off the Somali coast was almost eliminated by 2013 but longline catches have not recovered.

The sizes caught in the IO range from 30 cm to 180 cm fork length Figure 4. Intermediate age yellowfin are seldom taken in the industrial fisheries, but are abundant in some artisanal fisheries, mainly in the Arabian Sea. Newly recruited fish are primarily caught by the purse seine fishery on floating objects and the pole-and-line fishery in the Maldives. Males are predominant in the catches of larger fish at sizes larger than 150 cm (this is also the case in other oceans). Medium sized yellowfin concentrate for feeding in the Arabian Sea.

3 Model structure

3.1 Spatial stratification

The geographic area considered in the assessment is the IO, defined by the coordinates 40°S-25°N and 20°E-150°E. Earlier yellowfin stock assessments have adopted a five-area spatial structure (Langley, Herrera, and Million 2012), but several issues were identified for that structure. Since 2015, a four-area spatial structure is used for this stock (Figure 1). The Arabian Sea (area 1a) and western equatorial region (area 1b) make up the model area 1 but kept the fishery information separated (i.e., areas-as-fleet approach) to account for differences in selectivity between these sub-areas (Punt 2019). The spatial structure retains two regions that encompass the main year-round fisheries in the tropical area (areas 1 and 4) and two austral, subtropical regions where the longline fisheries occur more seasonally (areas 2 and 3).

The current spatial structure separates the purse-seine fishery in the northern Mozambique Channel (10-15°S) from the equatorial region, as the fishery in the northern Mozambique Channel exhibits strong seasonal variation in effort and operates differently from the equatorial region (Langley 2015). There is also a separation of the purse-seine fishery between the western and eastern tropical region with the current boundary between region 1b and region 4. In addition to the four-area configuration, we also evaluated two more spatial structures: one-area and two-area configurations (see more details in Appendix XX). The 2021 assessment also evaluated a modified version of the four-area structure (Fu et al. 2021), but there were some constraints to evaluate that configuration in the current assessment (see Section XX).

3.2 Temporal stratification

The time period covered by the assessment is 1950−2023, which represents the period for which catch data are available from the commercial fishing fleets. Langley (2015) suggested that the assessment results were not sensitive to the early catches from the model (pre-1972) and commencing the model in 1950 or 1972 (assuming unexploited equilibrium conditions) yielded very similar results.

The time step in the assessment model was quarter (i.e., three months duration, four quarters per year), representing a total of 296 model time steps. The definition of these time steps enabled recruitment to be estimated for each quarter to approximate the continuous recruitment of yellowfin in the equatorial regions. In addition, the quarterly model time step precluded the estimation of seasonal model parameters, particularly the movement parameters. Fu et al. (2018) explored an alternative annual/seasonal model structure which explicitly estimated seasonal movement dynamics. However, the alternative temporal structure did not yield substantially different results.

4 Model inputs

Catch and size information was provided by the IOTC Secretariat in a comma-separated values (CSV) format. These datasets and the metadata can be found online at the IOTC website: https://iotc.org/documents/WPTT/26AS/Data/01. The catch and size datasets were mainly composed of information about time (year and month), CPCs, gear type, school type, and grid code. In addition, the catch dataset had information on aggregated catch in weight (metric tons) and numbers, while the size dataset had information on the number of fish sampled per fork length bin (cm) and the score of reporting quality (RQ). The fork length bin width was 2 cm and the length bins spanned from 10 to 308 cm (i.e., a total of 150 length bins).

Before spatial and temporal aggregation, we processed the size data following the next steps:

1. The number of sampled fish from 198 to 308 cm was summed and then assigned it to the length bin 198 cm.
2. We converted the length bin width from 2 to 4 cm. To do so, we summed the number of sampled fish from pairs of length bins (e.g., 10 and 12 cm were summed and assigned to 10 cm, 14 and 16 cm were summed and assigned to 14 cm, and so on). After this conversion, we had a total of 48 length bins.

There was an error detected in the 2021 assessment when converting the length bin width from 2 to 4 cm, which only retained information on the number of sampled fish for length bins 10, 14, 18 cm, ..., and ignored the number of sampled fish for length bins 12, 16, 20 cm, ... from the size database. The impact of this error was evaluated during the model implementation.

4.1 Temporal aggregation

The monthly catch and size information was aggregated at a quarterly resolution by simply summing the catch values and the number of sampled fish per length bin, and averaging the RQ scores.

4.2 Spatial aggregation

The grid code was available for every observation in the catch and size datasets, which contained information on the grid dimensions, quadrant, and longitude and latitude of the corner of the grid. Using this information, we calculated the longitude and latitude of the center of each grid (called centroid hereafter). The catch dataset had information at a $5° \times 5°$ grid dimension. On the other hand, the IOTC Secretariat provided the size dataset with two distinct spatial treatments:

- *Irregular grids*: the size dataset had six main types of grid dimensions (see Table 1), although $\sim 97\%$ of observations were category 5 or 6. A seventh category of grid dimension was also present, but those observations were removed from the size database since it covered a very large and uncertain zone in the IO. This kind of spatial treatment was used in the 2021 assessment.
- *Regular grids*: the size data was provided at a $5° \times 5°$ grid dimension.

In order to spatially aggregate the catch and size data per model area (Figure 1), we followed two types of spatial aggregation as described below.

4.2.1 Simple aggregation

We assigned a model area for each observation based on the grid centroid. Note that this assignment differed by spatial treatment (irregular or regular grids) for the size dataset as shown in Figure 8 and Figure 9. Once the model area is assigned to each observation, we spatially aggregated the information by summing the catch values and the number of sampled fish per length bin and averaging the RQ values per model area. This approach was used in the 2021 assessment.

4.2.2 Catch-raised aggregation

This spatial aggregation method was performed only for the size dataset with a regular grid. Like the previous approach, we assigned a model area for each observation based on the grid centroid (Figure 9). To aggregate by model area, catch information was summed and size information was weighted by catch. In order to do this weighting, we first identified the catch (in numbers) that corresponded to a given size observation (i.e., year, quarter, grid, CPCs, and gear type). We found a perfect match for $\sim 78\%$ of cases but there were some size observations without catch. In order to fill in these catch gaps, we followed an imputation procedure with four levels:

- *Level 1*: Fill in catch gaps with the average catch per grid for a given year, quarter, CPCs, and gear type.
- *Level 2*: Fill in catch gaps with the average catch per grid for a given year, CPCs, and gear type.

- *Level 3*: Fill in catch gaps with the average catch per grid for a given year and gear type.
- *Level 4*: Fill in catch gaps with the average catch per grid for a given gear type.

Figure 10 shows the percentage of size observations that needed each level of imputation. Once catch information was assigned for every size information, we aggregated by model area by performing a catch-weighted sum of the number of sampled fish by length bin and a catch-weighted average of the RQ values.

4.3 Definition of fisheries

The assessment adopted the equivalent fisheries definitions used in the previous stock assessments (Table 2). These *fisheries* represent relatively homogeneous fishing units, with similar selectivity and catchability characteristics that do not vary greatly over time. Twenty-one fisheries were defined based on location (model area), time period, fishing gear, purse seine set type, and type of vessel in the case of longline fleet (Table 3).

The longline fishery was partitioned into two main components:

- *Freezing longline fisheries*, or all those using drifting longlines for which one or more of the following three conditions apply: (i) the vessel hull is made up of steel; (ii) vessel length overall of 30 m or greater; (iii) the majority of the catches of target species are preserved frozen or deep-frozen. A composite longline fishery was defined in each model area (LL 1–4) aggregating the longline catch from all freezing longline fleets (principally Japan and Taiwan).
- *Fresh-tuna longline fisheries*, or all those using drifting longlines and made of vessels (i) having fibreglass, fibre reinforced plastic, or wooden hull; (ii) having length overall less than 30 m; (iii) preserving the catches of target species fresh or in refrigerated seawater. A composite longline fishery was defined aggregating the longline catch from all fresh-tuna longline fleets (principally Indonesia and Taiwan) in region 4 (LF 4), which is where the majority of the fresh-tuna longliners have traditionally operated. The catches of yellowfin tuna recorded in regions 1 to 3 for fresh-tuna longliners, representing only 3% of the total catches over the time series, were assigned to area 4.

The purse-seine catch and effort data were apportioned into two separate method fisheries: catches from sets on associated schools of tuna (log and drifting FAD sets; *LS*) and from sets on unassociated schools (free schools; *FS*). Purse-seine fisheries operate within model areas 1a, 1b, 2 and 4 and separate purse-seine fisheries were defined in regions 1b, 2 and 4, with the limited catch, effort and length frequency data from region 1a reassigned to region 1b.

A single baitboat fishery was defined within region 1b (essentially the Maldives fishery). As with the purse-seine fishery, a small proportion of the total baitboat catch and effort occurs on the periphery of region 1b, within regions 1a and 4. The additional catch was assigned to the region 1b fishery.

Gillnet fisheries were defined in the Arabian Sea (region 1a), including catches by Iran, Pakistan, and Oman, and in region 4 (Sri Lanka and Indonesia). A very small proportion of the total gillnet catch and effort occurs in region 1b, with catches and effort reassigned to area 1a.

Three troll fisheries were defined, representing separate fisheries in regions 1b (Maldives), 2 (Comoros and Madagascar) and 4 (Sri Lanka and Indonesia). Moderate troll catches are also taken in regions 1a and 3, the catch and effort from this component of the fishery reassigned to the fisheries within region 1b and 4, respectively.

A handline fishery was defined within region 1a, principally representing catches by the Yemenis fleet. Moderate handline catches are also taken in regions 1b, 2 and 4, the catch and effort from these components of the fishery were reassigned to the fishery within region 1a.

For regions 1a and 4, a miscellaneous ("Other") fishery was defined comprising catches from artisanal fisheries other than those specified above (e.g. trawlers, small purse seines or seine nets, sport fishing and a range of small gears).

4.4 Catch

Catch data were compiled based on the fisheries definitions. An update of quarterly catches by fishery was provided by the IOTC Secretariat, including catches until December 2023. Overall, the time series of catches were quite similar to the catch series included in the 2021 assessment (Figure 11). The largest differences were observed for *OT 4* and *TR 4*, especially during the last two decades. Also, current catch estimates for *LL 3* are slightly larger than the previous assessment during 2008-2020. The changes are mostly attributed to revisions of catch estimation by the IOTC Secretariat.

4.5 Indices

4.5.1 Longline CPUE

Standardised CPUE indices (1975-2023) were derived using a hurdle generalized linear model (GLM) from longline catch and effort information provided by Japan, Korea, and Taiwan (Matsumoto et al. 2024). The data used for the standardization included operation date, fishing location, vessel ID, fishing effort (number of hooks per set), and catch in numbers. Cluster analyses of species composition data for each fleet and model area were used to separate datasets into fisheries understood to target different species. Selected clusters were then combined and standardized using GLMs. The log-transformed yellowfin catch per number of hooks set was the dependent variable of the positive model component, while the probability of catch rate being zero was the dependent variable in the binomial model component. In addition to the year and quarter variables, GLMs included covariates for 5° square location, cluster, and vessels ID. The data used in the GLM was subsampled from the operational data (\$ $10 - 30^\frown \times$\$ 5° grid. Moreover, data from regions 1a and 1b were combined as a single region. The CPUE indices was produced at an annual and quarterly time step and for each model area.

The CPUE index produced for region 1 was assigned to area 1b in the stock assessment model. For the regional longline fisheries, a common catchability coefficient (and selectivity) was estimated in the assessment model, thereby, linking the respective CPUE indices among regions. This significantly increases the power of the model to estimate the relative (and absolute) level of biomass among regions. However, as CPUE indices are essentially density estimates it is necessary to scale the CPUE indices to account for the relative abundance of the stock among regions. For example, a relatively small region with a very high average catch rate may have a lower level of total biomass than a large region with a moderate level of CPUE.

We determined regional scaling factors that incorporated both the size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass among regions.

This approach was also used in the 2021 assessment, and is similar to that used in the Western and Central Pacific Fisheries Commission (WCPFC) regionally disaggregated tuna assessments. Hoyle (2018) proposed a set of regional weighing factors for IO yellowfin based on aggregated longline catch effort data. The authors recommended the estimates by method '8' for the period 1979–1994 (referred to as '7994m8', see Table 2 of Hoyle (2018)) to be included in the current assessment. The relative scaling factors calculated for regions 1–4 are 1.674, 0.623, 0.455 and 1, respectively.

For each of the principal longline fisheries, the standardized CPUE index was normalized to the mean of the period for which the region scaling factors were derived (i.e., the GLM index from 1979–1994). The normalized GLM index was then scaled by the respective regional scaling factor to account for the regional differences in the relative level of exploitable longline biomass among regions (Figure 12).

A number of important trends are evident in the CPUE indices:

- The western tropical (region 1b) CPUE increased during the late 1970s and early 1980s, then suddenly declined from 1987 to 1990. After 1990, the CPUE in this region remained roughly stable until the late 2000s, that coincided with a number of piracy incidents in the western Indian Ocean (2008–2011). After that time, it remained close to the lowest level observed in that region but showed very large seasonal and annual variations. From 2020, we noticed a remarkable increase in CPUE values compared to the 2013-2019 period.
- The eastern tropical region 4 followed a similar pattern until 1990 but then declined steadily, and by 2016 was also close to the lowest level in the time series. The recent decline in CPUE in this region is consistent with a decline in the proportion of yellowfin in the combined tuna catch from the Japanese longline fleet in the eastern IO. It is unclear whether the change in species proportion is related to a decline in the abundance of yellowfin in the region (relative to the other species) or a regional change in the targeting of the fishing fleet. However, there is an indication that there has been a differential shift towards deeper longline gear (greater HBF) in the eastern IO since 2000 and this may indicate a shift in targeting toward bigeye tuna in this region (Hoyle pers. comm. additional JP LL analyses). Such factors may not be adequately accounted for in the standardisation of the yellowfin CPUE data.
- The CPUE indices in western temperate region 2 followed a similar pattern to the western tropical indices, with a decline until the late-1970s followed by an increase until the late 1980s, and subsequently a slow decline with significant variability. From 1990, the CPUE in this region has remained roughly stable, with no remarkable increase during the last years.
- The CPUE indices from region 3 are low compared to the other three regions reflecting the low regional scaling factor. However, the overall trend in the CPUE indices is broadly comparable to the other regions. The eastern temperate region 3 the pattern was similar to the western temperate area before 1979. After 1979 catch rates increased until the mid-2000's, but then declined rapidly and reached their lowest observed levels by 2016. In this region, we also noticed an increase in CPUE for the last years.
- There is an exceptionally high peak in CPUE indices 1976–78, which is also associated with a high uncertainty. Hoyle, Satoh, and Matsumoto (2017) showed that this discontinuity exists in Japanese, Taiwanese and Korean data, and in multiple regions in multiple oceans, and for both bigeye and yellowfin tuna. Hoyle, Satoh, and Matsumoto (2017) suggested

this is unlikely to be explained by changes to the population or catchability but may be associated with catch reporting and data management.

- The spike in the CPUE indices around 2012 in the west equatorial region (region 1) was evident for most fishing fleets. Several hypotheses have been proposed on what could have caused CPUE to have increased, including a return to fishing in areas that were most affected by piracy. However, further investigation is required.

The values and trend of LL CPUE used in the 2021 assessment and in this assessment were quite similar for all model areas before 1990 (Figure 14). After 1990, we noted large differences for model area 1b, where the current CPUE showed consistently larger values ($ $40%) than the 2021 CPUE, especially after 2005. For region 4, we also observed slightly larger 2024 CPUE values compared to the 2021 CPUE after 2005. However, this discrepancy was minimal for regions 2 and 3.

4.5.2 Purse seine CPUE indices

The European and associated flags purse seine fishing activities in the Indian Ocean during 1981–2020 have been monitored through the collection of logbooks and observer sampling. Standardised indices of the biomass of yellowfin caught by European purse seiners (Spain and France) from sets on free swimming schools (1991 – 2022) and sets on associated tuna schools (FOB, 2010 – 2022) were developed (Figure 13). The free school index was based on the application of a general additive mixed effect model with three components to model (Kaplan et al. 2024): i) the detection rate of free swimming schools per unit search time, ii) the probability that adult yellowfin are present in a set, and iii) the adult biomass per set given presence assuming a log-normal distribution. The FOB index was based on the application of two models: a generalized linear mixed model and a spatiotemporal model, both using a hurdle approach (Correa et al. 2024). These standardizations considered a comprehensive list of candidate covariates, including the effect of the technological improvement related to the use of echosounder buoys and environmental variables. The predicted CPUE over time was obtained using the *predict-then-aggregate* approach, which is considered best practice (Hoyle et al. 2024).

The FOB mainly informs the biomass of juvenile yellowfin, while the free-school index informs the biomass of the adult portion of the population in region 1b. The FOB index displays juvenile biomass fluctuations over the years, with larger values during 2013 and 2014, and a remarkable increase after 2020. On the other hand, the free school CPUE index showed a increase from the late 1990s until 2004, and then a dramatic decrease until 2009. From 2015, the free school index showed another dramatic decrease until 2018, and a slight recovery after that.

We evaluated the impact of incorporating the free school and FOB CPUE series as auxiliary indices (i.e., always in conjunction with the LL CPUE index) in the assessment model. In order to incorporate the free school index, we revised the region/fishery structure in which purse seine fisheries are separated into the small and large fish components (EXPAND THIS).

4.5.3 Effort creep

It is well recognised that the relationship between PS CPUE and abundance is unlikely be proportional, as the improvement of catch efficiency due to technology development is difficult to quantify, and the changes in catchability are not fully accounted for in the standardisation process. Effort creep can be defined as an unquantified increase in the average fishing power over time that disturbs the relationship of proportionality between the index and the stock trajectory (Hoyle 2024). These changes in catchability over time can affect CPUE indices, and therefore the outcomes of stock assessments. This is especially important for assessments that lack abundance indices from fishery-independent surveys, which includes the majority of the fisheries managed by tuna regional fishery management organizations (RFMOs).

For the case of longline fleets, technological advances include electronic devices to help navigate, communicate, and find target species. Synthetic materials allowed fishers to improve hooks and lines which increased probabilities of both hooking and landing. Satellite imagery improved search efficiency. Freezers increased the proportion of time spent on fishing grounds, while equipment for faster longline retrieval increased hooks set without affecting soak time (Hoyle 2024). In the 2021 yellowfin assessment in the IO, a sensitivity analysis was run during the WPTT meeting that included 1% effort creep per year for the entire period of the index, which resulted in changes in the stock depletion level. Based on the recommendations of Hoyle (2024), we evaluated two different levels of effort creep for the LL CPUE index in the current assessment: 0.5 and 1.5% per annum, which is associated with vessel turnover.

The WCPO assessments have often estimated substantial changes in PS FAD-associated fisheries (e.g., McKechnie, Pilling, and Hampton (2017)). Using a similar approach, Kolody (2018) estimated a catchability increase of approximately 1.25% per year for the standardised purse seine effort for yellowfin from sets on associated schools. Likewise, studies on the French fleet indicate a 10% increase in catch per set associated with echosounder use, equivalent to about 1% per annum, and a 1.7 – 4.0 % increase in efficiency (stable across time) arising from fishing their own floating objects (Wain et al. 2021). Based on the recommendations of Hoyle (2024), we evaluated two different levels of effort creep for both purse seine indices in the current assessment: 1.5 and 4.35% per annum.

4.6 Size data

Describe size data, length bins, catch raising, etc.

4.7 Age data

Describe age-length information, etc.

4.8 Tagging

Tagging information

5 Model parameters

5.1 Population dynamics

Parametrization of recruitment, growth, etc in SS.

5.2 Fishery dynamics

Selectivity principally.

5.3 Tagged fish

Tag reporting, mixing, etc.

5.4 Likelihood components

Weights, error structure, observation error, etc.

5.5 Parameter estimation and uncertainty

Hessian, max gradient, jitter analysis, likelihood profiles, etc.

5.6 Stock status

Related to MSY, depletion trends, Kobe, etc.

6 Model runs

6.1 Update from the last assessment

Describe stepwise model developtment, etc.

6.2 Sensitivity and structural uncertainty

Different steepness, M, etc, and spatial configurations.

7 Results

7.1 Fits

Describe fits to data.

7.2 Parameter estimates

Describe parameter estimates.

7.3 Time series

Recruitment, SSB, etc.

7.4 Sensitivity

Describe sensitivity analyses.

8 Discussion and conclusions

Discuss. Recommendations for future assessments.

9 Acknowledgements

Write your acknowledgements.

10 Tables

Table 1: Grid size categories in the raw catch and LF datasets.

Grid type	Resolution (latitude $\times$ longitude)
1	$30° \times 30°$
2	$10° \times 20°$
3	$10° \times 10°$
4	$20° \times 20°$
5	$1° \times 1°$
6	$5° \times 5°$

Table 2: Fishery classification used in the assessment.

Fishery code	Gear
GI	Gillnet
HD	Handline
LL	Longline
OT	Others
BB	Baitboat
FS	Purse seine, free school
LS	Purse seine, log school
TR	Troll
LF	Longline (fresh tuna)

Table 3: Fishery definition in the assessment configuration with 4 areas.

Fishery number	Fishery code and region
1	GI 1a
2	HD 1a
3	LL 1a
4	OT 1a
5	BB 1b
6	FS 1b
7	LL 1b
8	LS 1b
9	TR 1b
10	LL 2
11	LL 3
12	GI 4
13	LL 4
14	OT 4
15	TR 4
16	FS 2
17	LS 2
18	TR 2
19	FS 4
20	LS 4
21	LF 4

11 Figures

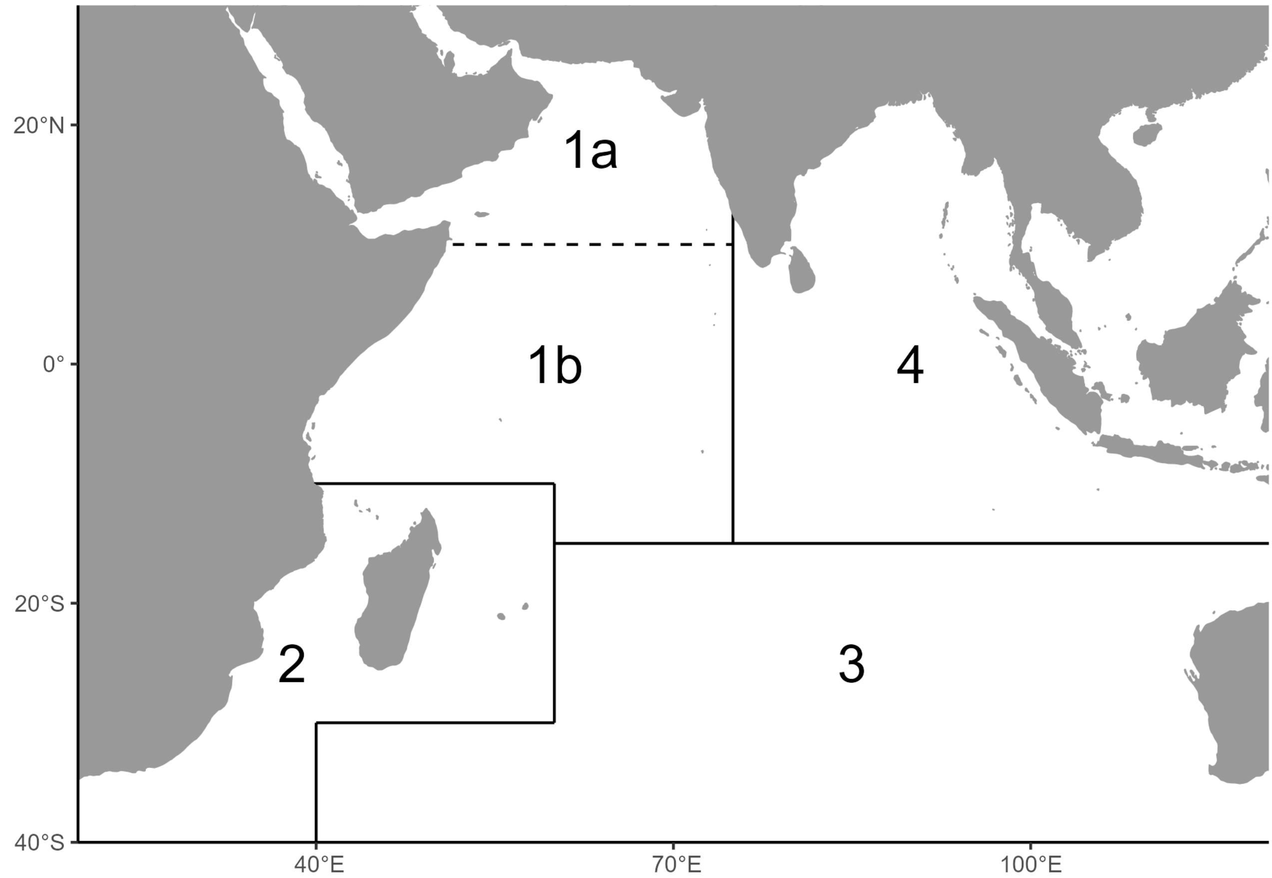
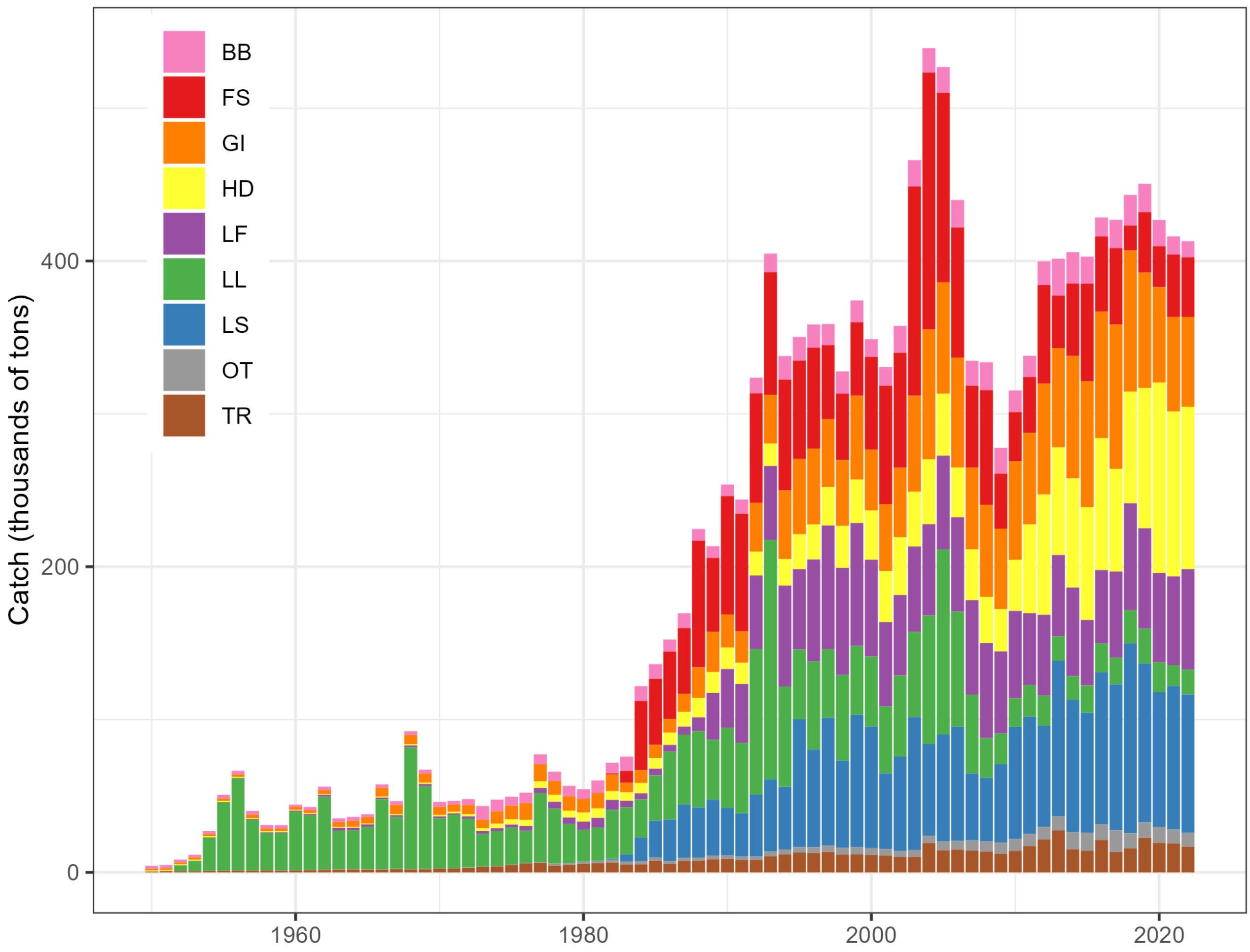


Figure 1: Add your caption here.



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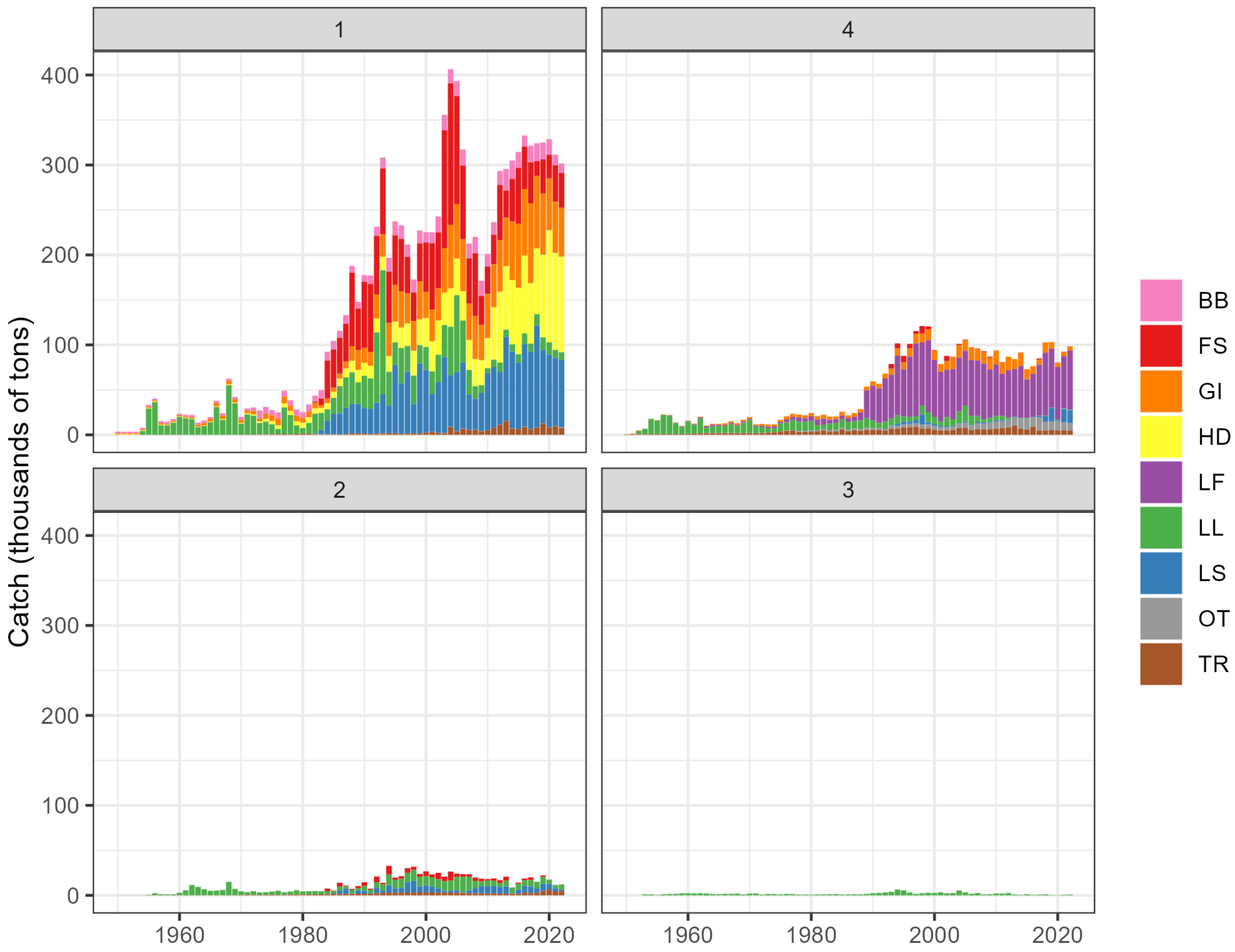


Figure 3: Add your caption here.

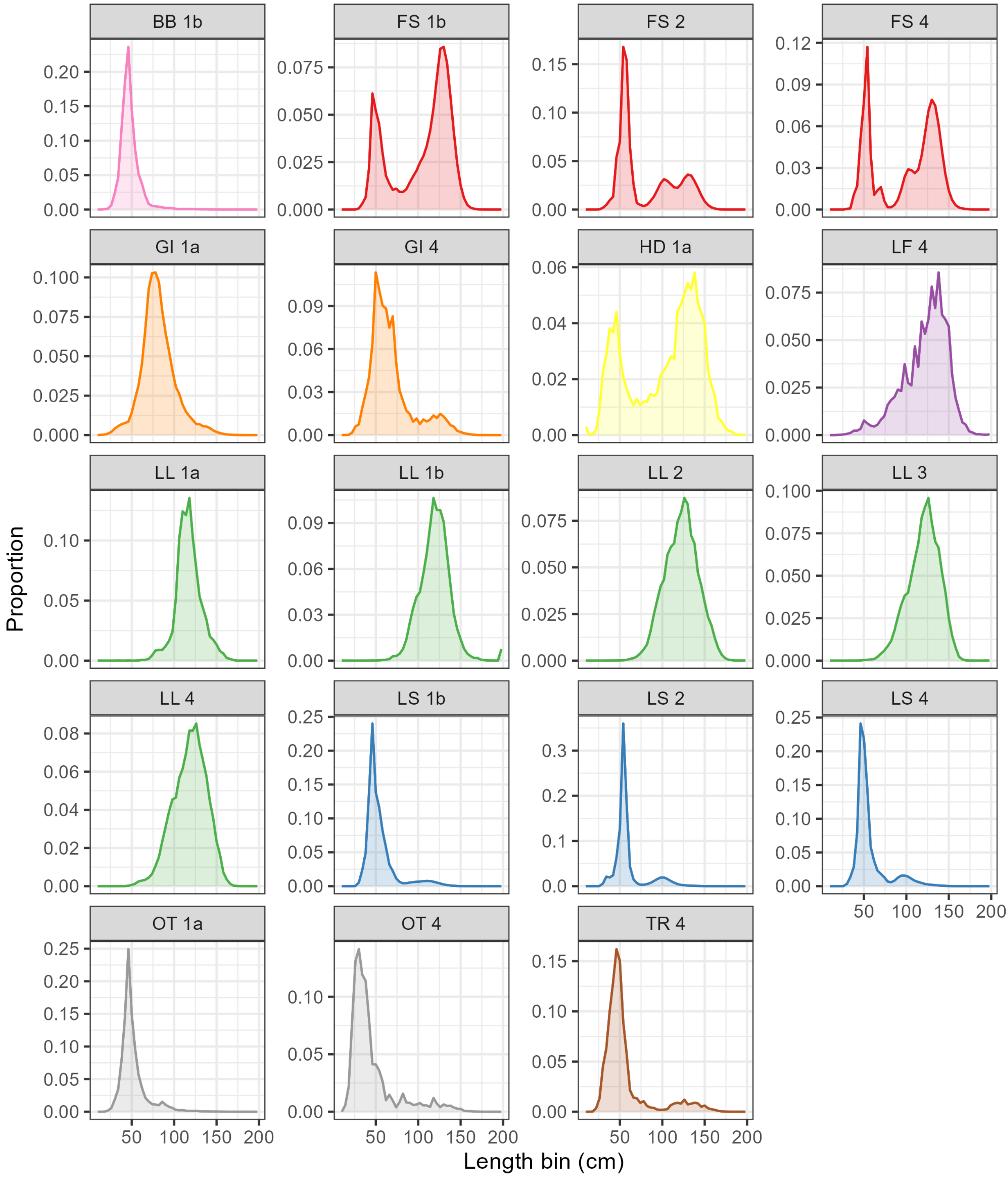
12 Appendix

12.1 Acronyms and Abbreviations

Include a table with acronyms (e.g., GLMM, SS, etc.)

12.2 Likelihood profiles

12.3 Retrospective analyses



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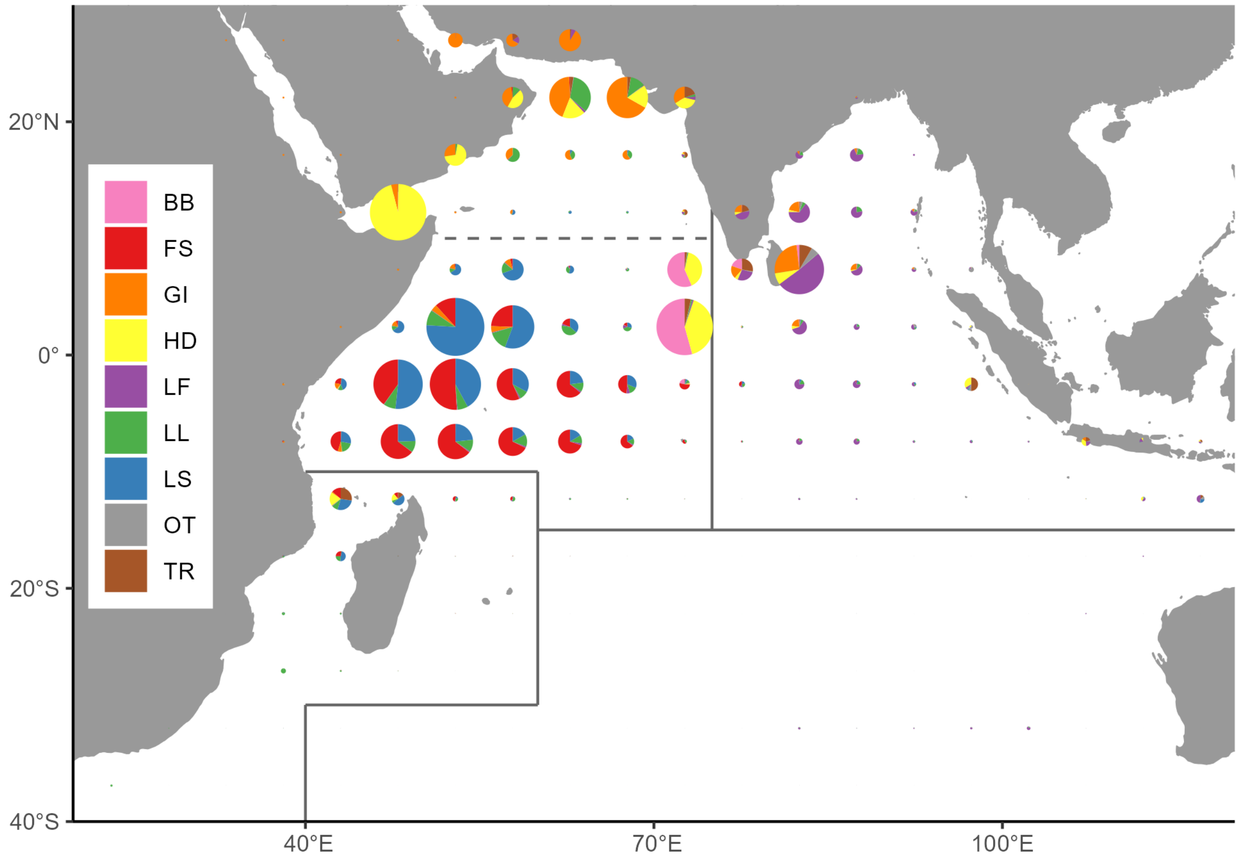

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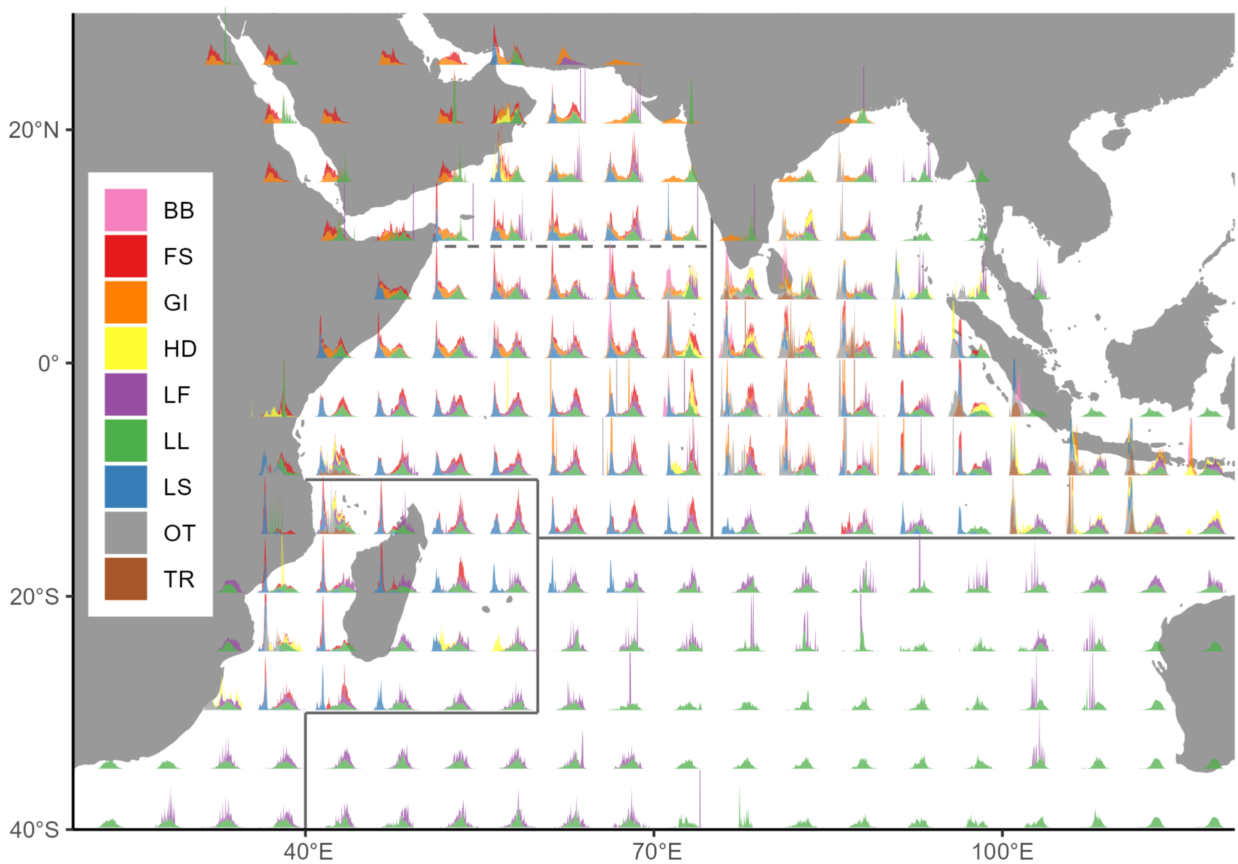

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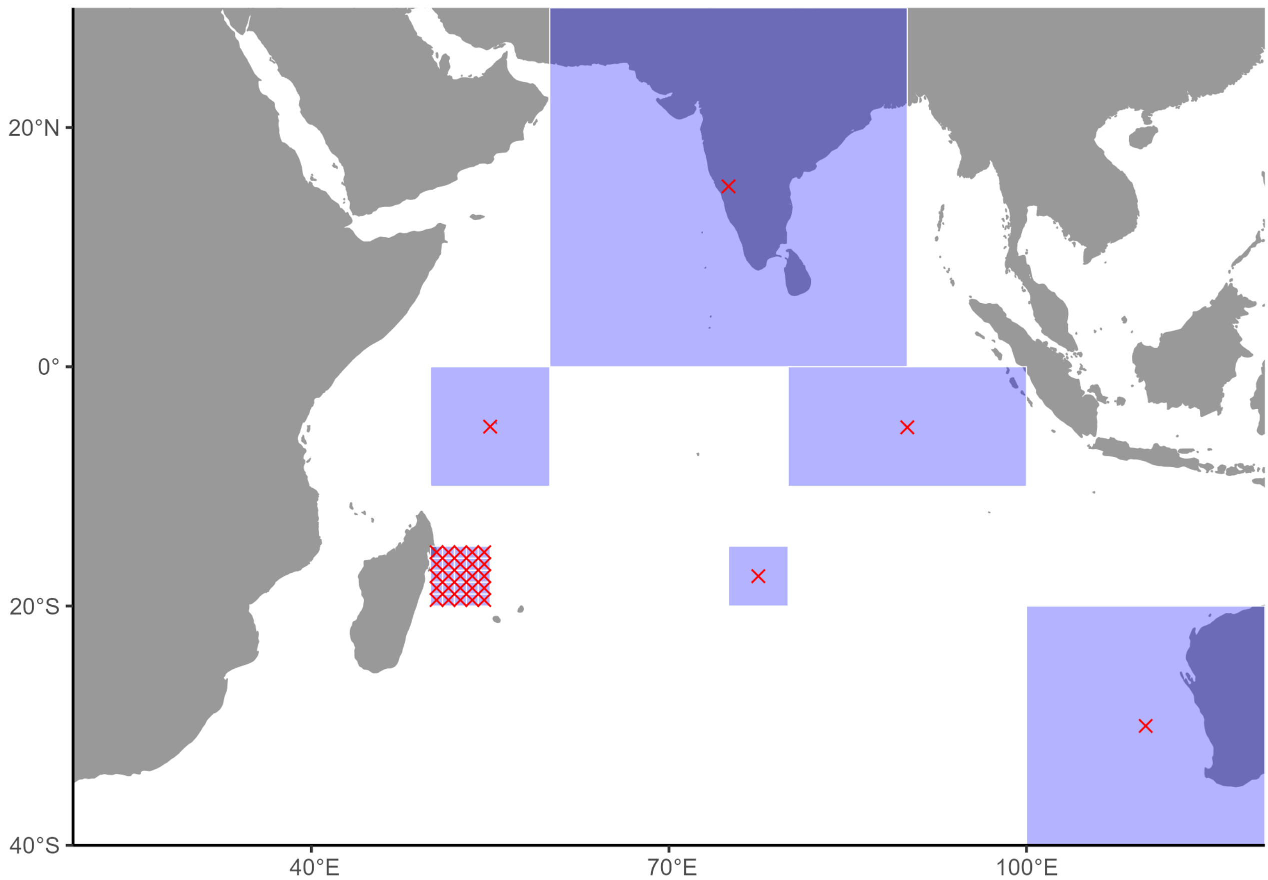

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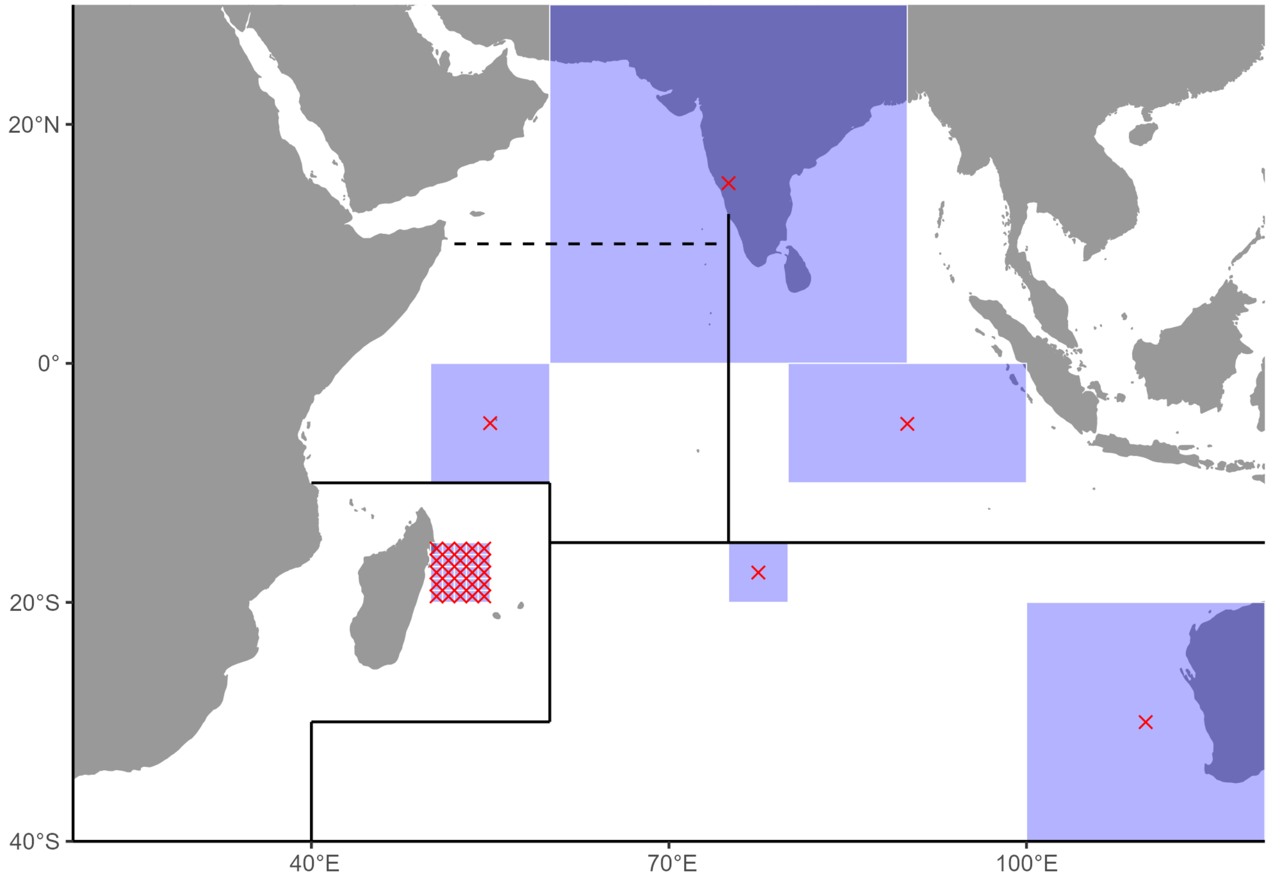

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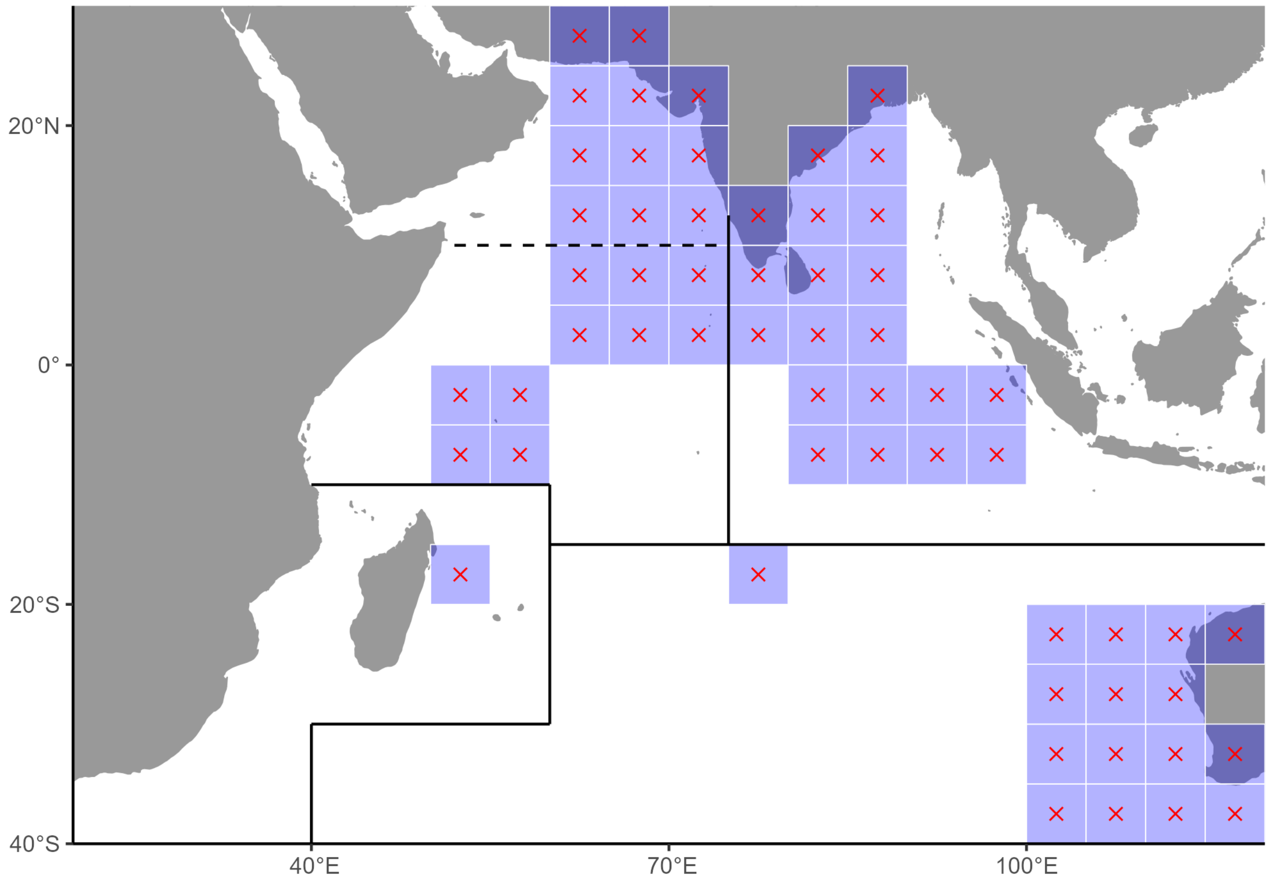

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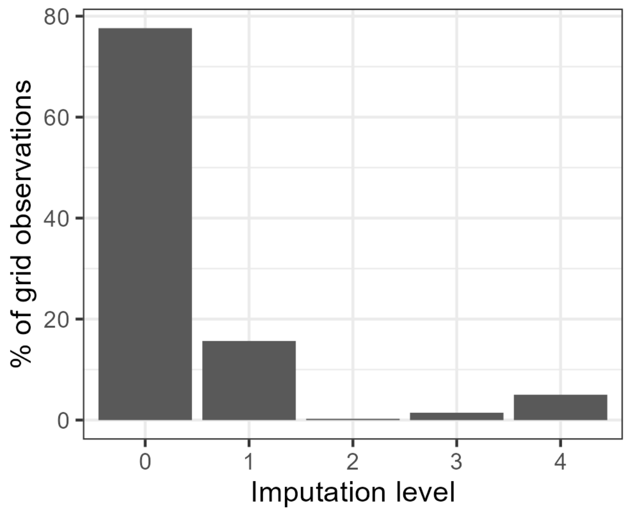

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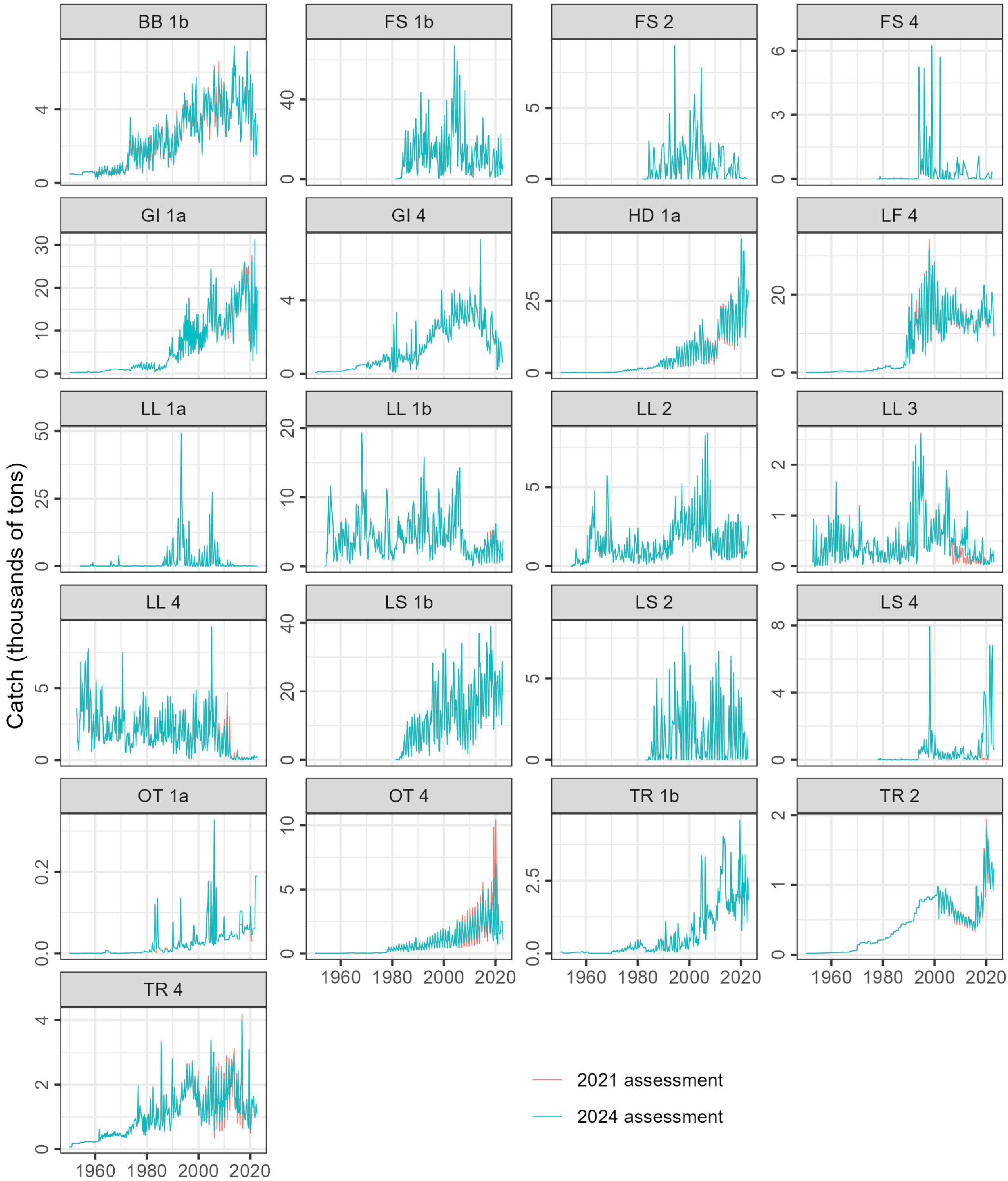

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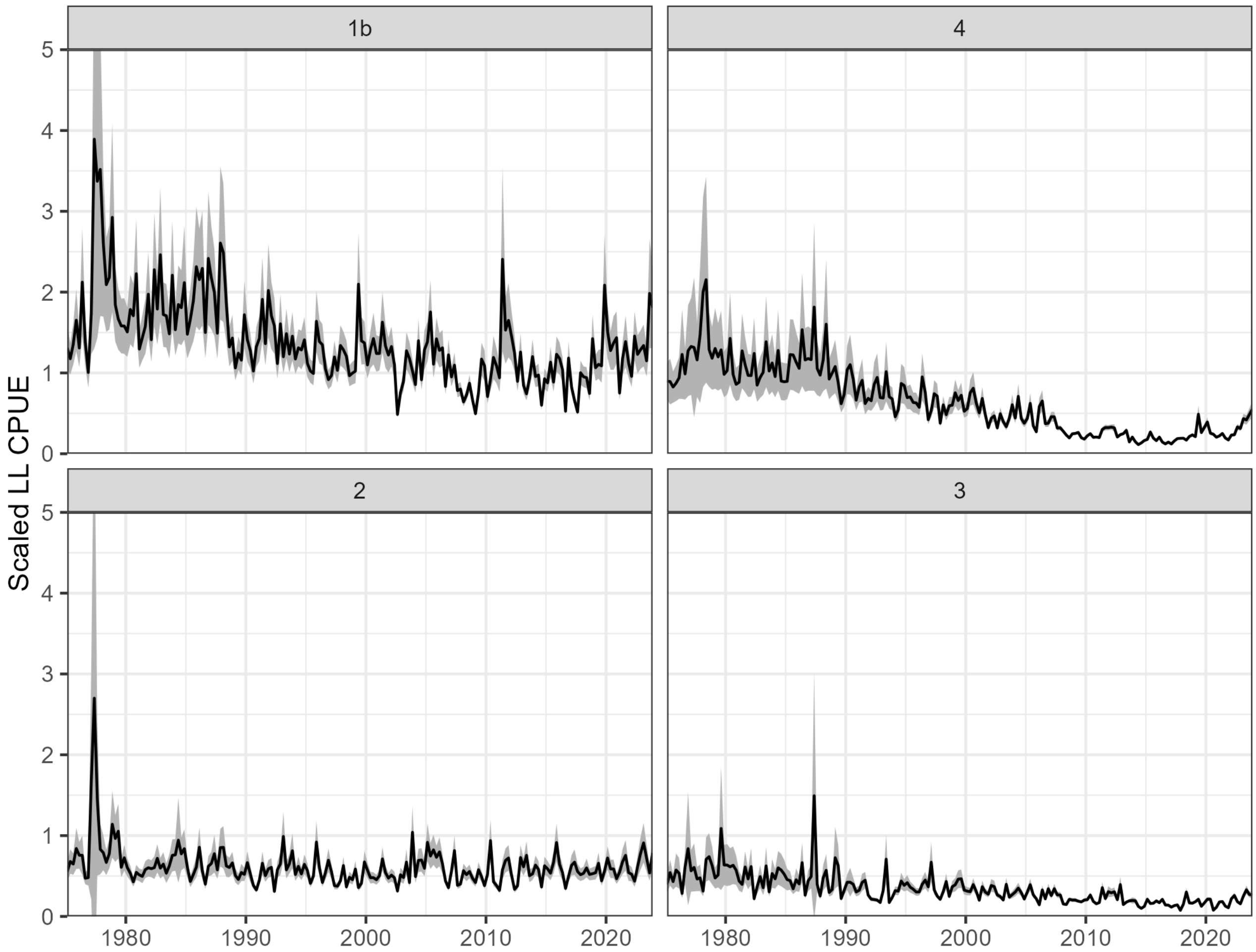

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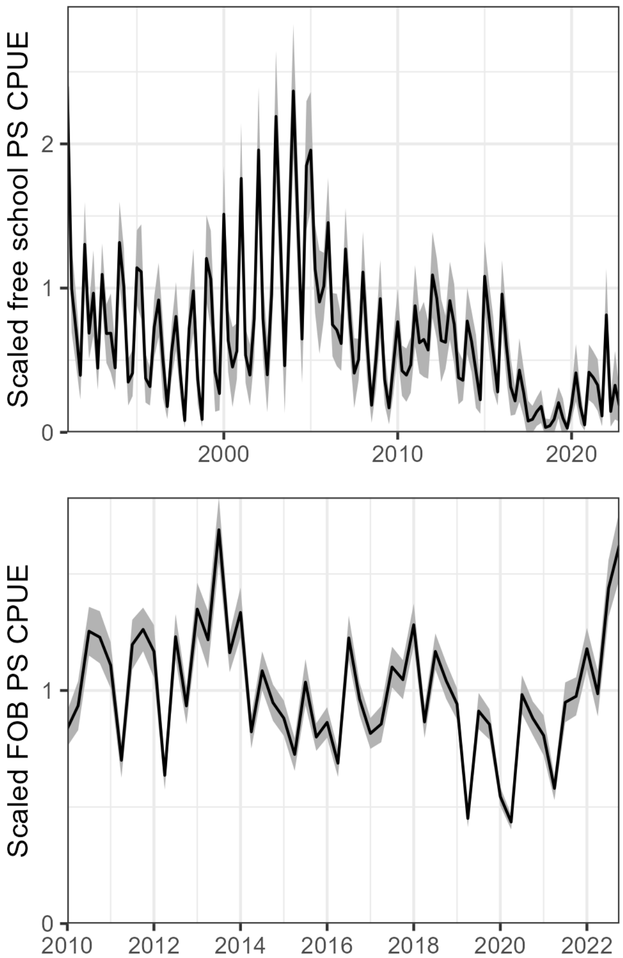

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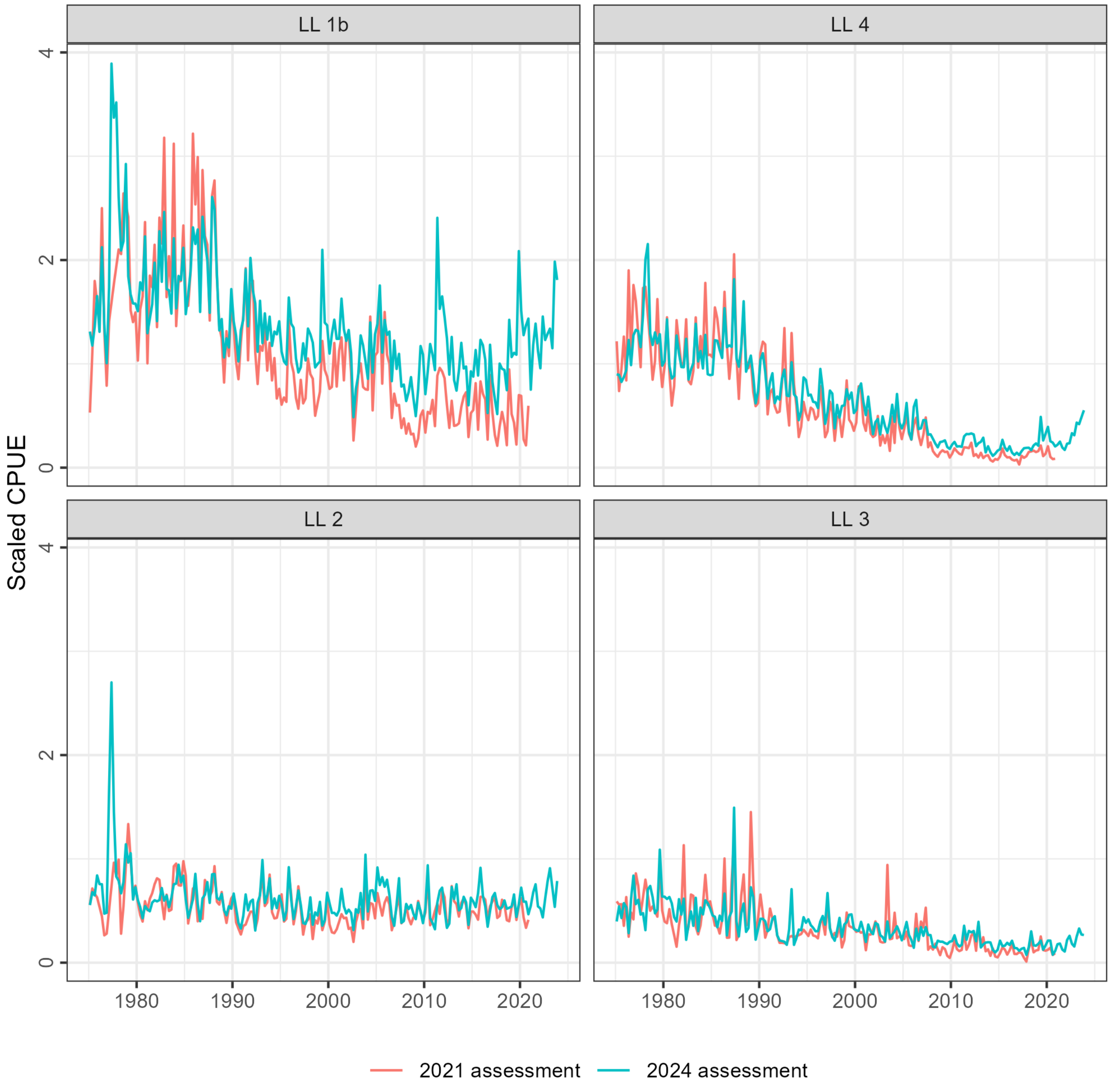

Figure 14: Add your caption here.

References

Artetxe-Arrate, Iraide, Igaratza Fraile, Patricia Lastra-Luque, Jessica Farley, Naomi Clear, Umair Shahid, S. Adbul-Razzaue, et al. in review. "Otolith Stable Isotopes Highlight the Importance of Local Nursery Areas as the Origin of Recruits to Yellowfin Tuna (Thunnus Albacares) Fisheries in the Western Indian Ocean." *Fisheries Research*, in review.

Artetxe-Arrate, Iraide, Igaratza Fraile, Francis Marsac, Jessica H. Farley, Naiara Rodriguez-Ezpeleta, Campbell R. Davies, Naomi P. Clear, Peter Grewe, and Hilario Murua. 2021. "A Review of the Fisheries, Life History and Stock Structure of Tropical Tuna (Skipjack Katsuwonus Pelamis, Yellowfin Thunnus Albacares and Bigeye Thunnus Obesus) in the Indian Ocean." In *Advances in Marine Biology*, 88:39–89. Elsevier. https://doi.org/10.1016/bs.amb.2020.09.002.

Correa, Giancarlo M., Jon Uranga, David Kaplan, Gorka Merino, and Lourdes Ramos. 2024. "Standardized Catch Per Unit Effort of Yellowfin Tuna in the Indian Ocean for the European Purse Seine Fleet Operating on Floating Objects." IOTC-2024-WPTT26(DP)-11rev1. Indian Ocean Tuna Comission.

Dammannagoda, Sudath T., David A. Hurwood, and Peter B. Mather. 2008. "Evidence for Fine Geographical Scale Heterogeneity in Gene Frequencies in Yellowfin Tuna (Thunnus Albacares) from the North Indian Ocean Around Sri Lanka." *Fisheries Research* 90 (1-3): 147–57. https://doi.org/10.1016/j.fishres.2007.10.006.

Duffy, Leanne M., Petra M. Kuhnert, Heidi R. Pethybridge, Jock W. Young, Robert J. Olson, John M. Logan, Nicolas Goñi, et al. 2017. "Global Trophic Ecology of Yellowfin, Bigeye, and Albacore Tunas: Understanding Predation on Micronekton Communities at Ocean-Basin Scales." *Deep Sea Research Part II: Topical Studies in Oceanography* 140 (June): 55–73. https://doi.org/10.1016/j.dsr2.2017.03.003.

Farley, Jessica H., Kyne KrusicGolub, Paige Eveson, Patricia Luque, Igaratza Fraile, Iraide Artetxe-Arrate, Iker Zudaire, et al. 2023. "Updating the Estimation of Age and Growth of Yellowfin Tuna (Thunnus Albacares) in the Indian Ocean Using Otoliths." IOTC-2023-WPTT25-20. Indian Ocean Tuna Comission.

Froese, Rainer, and Daniel Pauly. 2024. "FishBase." World {{Wide Web}} Electronic Publication. www.fishbase.org.

Fu, Dan, Adam D. Langley, Gorka Merino, and Agurtzane Urtizberea. 2018. "Preliminary Indian Ocean Yellowfin Tuna Stock Assessment 1950-2017 (Stock Synthesis)." IOTC–2018–WPTT20–33. Indian Ocean Tuna Comission.

Fu, Dan, Agurtzane Urtizberea Ijurco, Massimiliano Cardinale, Richard D Methot, Simon D. Hoyle, and Gorka Merino. 2021. "Preliminary Indian Yellowfin Tuna Stock Assessment 1950-2020 (Stock Synthesis)." IOTC-2021-WPTT23-12. Indian Ocean Tuna Comission.

Gaertner, Daniel, and Jean Pierre Hallier. 2015. "Tag Shedding by Tropical Tunas in the Indian Ocean and Other Factors Affecting the Shedding Rate." *Fisheries Research* 163 (March): 98–105. https://doi.org/10.1016/j.fishres.2014.02.025.

Grewe, Peter, Pierre Feutry, Scott Foster, Aulich, Matt Lansdell, Scott Cooper, Naomi Clear, et al. 2020. "Genetic Population Connectivity of Yellowfin Tuna in the Indian Ocean from the PSTBS-IO Project." IOTC-2020-WPTT22(AS)12_REV1. Seychelles: Indian Ocean Tuna Comission.

Hosseini, S A, and F Kaymaram. 2016. "Investigations on the Reproductive Biology and Diet of Yellowfin Tuna, Thunnus Albacares, (Bonnaterre, 1788) in the Oman Sea." *Journal of Applied Icthyology* 32: 310–17. https://doi.org/10.1111/jai.12907.

Hoyle, Simon D. 2018. "Indian Ocean Tropical Tuna Regional Scaling Factors That Allow for Seasonality and Cell Areas." IOTC-2018-WPM09-13. Indian Ocean Tuna Comission.

———. 2024. "Effort Creep in Longline and Purse Seine CPUE and Its Application in Tropical Tuna Assessments." IOTC-2024-WPTT26(DP)-16. Indian Ocean Tuna Comission.

Hoyle, Simon D., Robert A. Campbell, Nicholas D. Ducharme-Barth, Arnaud Grüss, Bradley R. Moore, James T. Thorson, Laura Tremblay-Boyer, Henning Winker, Shijie Zhou, and Mark N. Maunder. 2024. "Catch Per Unit Effort Modelling for Stock Assessment: A Summary of Good Practices." *Fisheries Research* 269 (January): 106860. https://doi.org/10.1016/j.fishres.2023.106860.

Hoyle, Simon D., Keisuke Satoh, and Takayuki Matsumoto. 2017. "Exploring Possible Causes of Historical Discontinuities in Japanese Longline CPUE." IOTC-2017-WPTT19-33. Indian Ocean Tuna Comission.

IOTC, Secretariat. 2021. "Review of Yellowfin Tuna Statistical Data." IOTC-2021-WPTT23(DP)-07_Rev1. Indian Ocean Tuna Comission.

Kaplan, David, Giancarlo M Correa, Lourdes Ramos, Antoine Duparc, Jon Uranga, Josu Santiago, Laurent Floch, et al. 2024. "Standardized CPUE Abundance Indices for Adult Yellowfin Tuna Caught in Free-Swimming School Sets by the European Purse-Seine Fleet in the Indian Ocean, 1991-2022." IOTC-2024-WPTT26(DP)-13rev2.

Kolody, D. 2018. "Estimation of Indian Ocean Skipjack Purse Seine Catchability Trends from Bigeye and Yellowfin Assessments." IOTC–2018–WPTT20–32. Indian Ocean Tuna Comission.

Krishnan, Silambarasan, Tiburtius Antony Pillai, John Chembian Antony Rayappan, Tharumar Yagappan, and Jeyabaskaran Rajapandian. 2024. "Diet Composition and Feeding Habits of Yellowfin Tuna *Thunnus Albacares* (Bonnaterre, 1788) from the Bay of Bengal." *Aquatic Living Resources* 37: 10. https://doi.org/10.1051/alr/2024008.

Kumar, Mamidi Satish, and Shubhadeep Ghosh. 2022. "Reproductive Dynamics of Yellowfin Tuna, Thunnus Albacares (Bonnaterre 1788) Exploited from Western Bay of Bengal." *Thalassas: An International Journal of Marine Sciences* 38: 1003–12. https://doi.org/10.1007/s41208-022-00429-1.

Kunal, Swaraj Priyaranjan, Girish Kumar, Maria Rosalia Menezes, and Ram Murti Meena. 2013. "Mitochondrial DNA Analysis Reveals Three Stocks of Yellowfin Tuna Thunnus Albacares (Bonnaterre, 1788) in Indian Waters." *Conservation Genetics* 14 (1): 205–13. https://doi.org/10.1007/s10592-013-0445-3.

Lan, Kuo-Wei, Yi-Jay Chang, and Yan-Lun Wu. 2020. "Influence of Oceanographic and Climatic Variability on the Catch Rate of Yellowfin Tuna (Thunnus Albacares) Cohorts in the Indian Ocean." *Deep Sea Research Part II: Topical Studies in Oceanography* 175 (May): 104681. https://doi.org/10.1016/j.dsr2.2019.104681.

Lan, Kuo-Wei, Karen Evans, and Ming-An Lee. 2013. "Effects of Climate Variability on the Distribution and Fishing Conditions of Yellowfin Tuna (Thunnus Albacares) in the Western Indian Ocean." *Climatic Change* 119 (1): 63–77. https://doi.org/10.1007/s10584-012-0637-8.

Langley, Adam D. 2015. "Stock Assessment of Yellowfin Tuna in the Indian Ocean Using Stock Synthesis." IOTC–2015–WPTT17–30. Indian Ocean Tuna Comission.

———. 2016. "An Update of the 2015 Indian Ocean Yellowfin Tuna Stock Assessment for 2016." IOTC-2016-WPTT18-27. Indian Ocean Tuna Comission.

Langley, Adam D., John Hampton, Miguel Herrera, and Julien Million. 2008. "Preliminary Stock Assessment of Yellowfin Tuna in the Indian Ocean Using MULTIFAN-CL." IOTC-2008-WPTT-10. Indian Ocean Tuna Comission.

Langley, Adam D., Miguel Herrera, Jean-Pierre Hallier, and Julien Million. 2009. "Stock Assessment of Yellowfin Tuna in the Indian Ocean Using MULTIFAN-CL." IOTC-2009-WPTT-10. Indian Ocean Tuna Comission.

Langley, Adam D., Miguel Herrera, and Julien Million. 2010. "Stock Assessment of Yellowfin Tuna in the Indian Ocean Using MULTIFAN-CL." IOTC-2010-WPTT-23. Indian Ocean Tuna Comission.

———. 2011. "Stock Assessment of Yellowfin Tuna in the Indian Ocean Using MULTIFAN-CL." IOTC-2011-WPTT-13. Indian Ocean Tuna Comission.

———. 2012. "Stock Assessment of Yellowfin Tuna in the Indian Ocean Using MULTIFAN-CL." IOTC-2012-WPTT-14-38 Rev_1. Indian Ocean Tuna Comission.

Matsumoto, Takayuki, Keisuke Satoh, Wen-Pei Tsai, Sheng-Ping Wang, Jung-Hyun Lim, Heewon Park, and Sung Il Lee. 2024. "Joint Longline CPUE for Yellowfin Tuna in the Indian Ocean by the Japanese, Korean and Taiwanese Longline Fishery." IOTC-2024-WPTT26(DP)-14. Indian Ocean Tuna Comission.

Maunder, Mark, Carolina V. Minte-Vera, Adam D. Langley, and Daniel Howell. 2023. "Independent Review of Recent IOTC Yellowfin Tuna Assessment." IOTC-2023-WPTT25-13_Rev1. Indian Ocean Tuna Comission.

McKechnie, S., G. Pilling, and John Hampton. 2017. "Stock Assessment of Bigeye Tuna in the Western and Central Pacific Ocean." WCPFC-SC13-2017/SA-WP-05. Western and Central Pacific Fisheries Commission.

Ménard, Frédéric, Anne Lorrain, Michel Potier, and Francis Marsac. 2007. "Isotopic Evidence of Distinct Feeding Ecologies and Movement Patterns in Two Migratory Predators (Yellowfin Tuna and Swordfish) of the Western Indian Ocean." *Marine Biology* 153 (2): 141–52. https://doi.org/10.1007/s00227-007-0789-7.

Methot, Richard D. 2019. "Recommendations on the Configuration of the Indian Ocean Yellowfin Tuna Stock Assessment Model."

Methot, Richard D., and Chantell R. Wetzel. 2013. "Stock Synthesis: A Biological and Statistical Framework for Fish Stock Assessment and Fishery Management." *Fisheries Research* 142 (May): 86–99. https://doi.org/10.1016/j.fishres.2012.10.012.

Moore, Bradley R, Pratiwi Lestari, Scott C Cutmore, Craig Proctor, and Robert J G Lester. 2019. "Movement of Juvenile Tuna Deduced from Parasite Data." Edited by James Watson. *ICES Journal of Marine Science* 76 (6): 1678–89. https://doi.org/10.1093/icesjms/fsz022.

Muhling, Barbara A., John T. Lamkin, Francisco Alemany, Alberto García, Jessica Farley, G. Walter Ingram, Diego Alvarez Berastegui, Patricia Reglero, and Raul Laiz Carrion. 2017. "Reproduction and Larval Biology in Tunas, and the Importance of Restricted Area Spawning Grounds." *Reviews in Fish Biology and Fisheries* 27 (4): 697–732. https://doi.org/10.1007/s11160-017-9471-4.

Nishida, Tom, and Hiroshi Shono. 2005. "Stock Assessment of Yellowfin Tuna (Thunnus Albacares) Resources in the Indian Ocean by the Age Structured Production Model (ASPM) Analyses." IOTC-2005-WPTT-09. Indian Ocean Tuna Comission.

———. 2007. "Stock Assessment of Yellowfin Tuna (Thunnus Albacares) in the Indian Ocean by the Age Structured Production Model(ASPM) Analyses." IOTC-2007-WPTT-12. Indian Ocean Tuna Comission.

Nootmorn, Praulai, Anchalee Yakoh, and Kannokwan Kawises. 2005. "Reproductive Biology of Yellowfin Tuna in the Eastern Indian Ocean." IOTC-2005-WPTT-14. Indian Ocean Tuna Comission.

Pecoraro, C., I. Zudaire, N. Bodin, H. Murua, P. Taconet, P. Díaz-Jaimes, A. Cariani, F. Tinti, and E. Chassot. 2017. "Putting All the Pieces Together: Integrating Current Knowledge of the Biology, Ecology, Fisheries Status, Stock Structure and Management of Yellowfin Tuna (Thunnus Albacares)." *Reviews in Fish Biology and Fisheries* 27 (4): 811–41. https://doi.org/10.1007/s11160-016-9460-z.

Punt, André E. 2019. "Spatial Stock Assessment Methods: A Viewpoint on Current Issues and

Assumptions." *Fisheries Research* 213 (May): 132–43. https://doi.org/10.1016/j.fishres.2019.01.014.

Roger, Claude. 1994. "Relationships Among Yellowfin and Skipjack Tuna, Their Prey-Fish and Plankton in the Tropical Western Indian Ocean." *Fisheries Oceanography* 3 (2): 133–41. https://doi.org/10.1111/j.1365-2419.1994.tb00055.x.

Sabarros, Philippe, Evgeny Romanov, and Pascal Bach. 2015. "Vertical Behavior and Habitat Preferences of Yellowfin and Bigeye Tuna in the South West Indian Ocean Inferred from PSAT Tagging Data." IOTC–2015–WPTT17–42 Rev_1. Indian Ocean Tuna Comission.

Urtizberea, Agurtzane, Massimiliano Cardinale, Henning Winker, Richard D. Methot, Dan Fu, Toshihide Kitakado, Carmen Fernandez, and Gorka Merino. 2020. "Towards Providing Scientific Advice for Indian Ocean Yellowfin in 2020." IOTC-2020-WPTT22(AS)-21. Indian Ocean Tuna Comission.

Urtizberea, Agurtzane, Dan Fu, Gorka Merino, Richard D Methot, Massimiliano Cardinale, Henning Winker, John Walter, and Hilario Murua. 2019. "Preliminary Assessment of Indian Ocean Yellowfin Tuna 1950-2018 (Stock Synthesis, V3.30)." IOTC-2019-WPTT21-50. Indian Ocean Tuna Comission.

Wain, Gwenaëlle, Loreleï Guéry, David Michael Kaplan, and Daniel Gaertner. 2021. "Quantifying the Increase in Fishing Efficiency Due to the Use of Drifting FADs Equipped with Echosounders in Tropical Tuna Purse Seine Fisheries." Edited by Richard O'Driscoll. *ICES Journal of Marine Science* 78 (1): 235–45. https://doi.org/10.1093/icesjms/fsaa216.

Zudaire, Iker, Iraide Artetxe-Arrate, Jessica H. Farley, Hilario Murua, Deniz Kukul, Annie Vidot, Shoaib Razzaque, et al. 2022. "Preliminary Estimates of Sex Ratio, Spawning Season, Batch Fecundity and Length at Maturity for Indian Ocean Yellowfin Tuna." IOTC-2022-WPTT24(DP)-09. Indian Ocean Tuna Comission.

Zudaire, Iker, Hilario Murua, Maitane Grande, and Nathalie Bodin. 2013. "Reproductive Potential of Yellowfin Tuna (Thunnus Albacares) in the Western Indian Ocean." *Fishery Bulletin* 111 (3): 252–64. https://doi.org/10.7755/FB.111.3.4.