



APPLICATION OF PER-RECRUIT AND LENGTH-BASED DATA-LIMITED ASSESSMENT METHODS TO PELAGIC SHARKS IN THE INDIAN OCEAN

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Discussions: The purpose of the paper is to inform the WPEB that per-recruit (YPR, SPR) and length-based data-limited assessment methods (LB-SPR, FISHBLICC) have been applied to priority and data-limited pelagic sharks in the Indian Ocean, characterising the available size-composition data and providing preliminary indications of selectivity, biological reference points and relative stock status for these species.

Feedback: The authors of the paper request review, comments and feedback on the data inputs and life-history parameters compiled, the assumptions and configurations used in the analyses, and on the interpretation of the resulting reference points and SPR estimates.

Conclusion: The authors of the paper seek confirmation that the work provides useful, even if preliminary, findings on the status of those data-limited shark species in the Indian Ocean, and that the approach should be continued, further explored and expanded to additional species.

Recommendations: The paper seeks endorsement of a recommendation from the WPEB for CPCs to: 1) improve region-specific life-history information on pelagic sharks, 2) strengthen size-composition sampling and reporting to IOTC, and 3) improve the quantification of discard rates and post-release mortality, so that a more complete quantification of fishing mortality can be achieved.

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Abstract

In this study, we applied a set of data-limited methods to pelagic shark species that are a priority for the IOTC/WPEB, providing a preliminary indication of the relative vulnerability and status of these data-limited sharks in the Indian Ocean. We focused on the 2026 priority shark species (silky shark, oceanic whitetip, and scalloped hammerhead) and included also the blue shark as a data-moderate species for which full assessments are carried out, to be used mostly as a comparison. The methods included per-recruit analyses, namely Yield Per Recruit (YPR) and Spawning Potential Ratio (SPR), and two length-based data-limited assessments, namely Length-Based Spawning Potential Ratio (LB-SPR) and Bayesian Length Interval Catch Curve Analysis (FISHBLICC). The analyses used size-frequency data from the IOTC databases, together with compiled life-history parameters. Across all species, the yield-based reference point $F_{0.1}$ exceeded the spawning-based target F at SPR40 in almost all scenarios, indicating that yield-based reference points might not be the most adequate or precautionary for these low-productivity shark species. LB-SPR estimates indicated that current fishing mortality on blue shark longline is likely between the SPR 40% target and SPR 20% limit, that the silky shark longline fishery is likely close to the SPR 20% limit, while the silky shark purse seine fishery showed spawning potential much lower than the SPR 20% limit. The FISHBLICC results are largely comparable to the LB-SPR.

Keywords

Data-limited methods, Indian Ocean, pelagic sharks, reference points, size-based methods, spawning potential ratio.

1. Introduction

Within the IOTC, several pelagic shark species have been identified as priorities for assessment and management. Among these, the silky shark (*Carcharhinus falciformis*, FAL), oceanic whitetip shark (*Carcharhinus longimanus*, OCS), and scalloped hammerhead shark (*Sphyrna lewini*, SPL) have been identified by the Working Party on Ecosystems and Bycatch (WPEB) to be focused during 2026. To date, the WPEB has only conducted analytical assessments for two pelagic shark species, namely blue shark (*Prionace glauca*, BSH) (Rice, 2025) and shortfin mako (*Isurus oxyrinchus*, SMA) (Coelho, et al., 2024), while the remaining are in general considered to be data-limited and to date no assessments have been carried out.

For those species, the data typically required to conduct full analytical assessments (i.e., reliable catch series, indices of abundance and biological data) are either absent or highly incomplete. This has motivated the application and exploration of data-limited assessment methods, which require fewer inputs and can provide indications of stock status from more readily available information such as life-history parameters and size-composition data (Hordyk et al., 2015; Medley, 2025). Per-recruit analyses (YPR: yield per recruit and SPR: spawning potential ratio) and length-based data-limited assessment methods (LB-SPR and FISHBLICC) are among those methods and are being increasingly applied to data-limited elasmobranch stocks.

In this paper, we apply per-recruit and length-based methods to four pelagic shark species in the Indian Ocean (BSH, FAL, OCS, and SPL). The specific objectives of the paper are to: 1) characterize the size composition data available by species and gear, 2) estimate yield- and spawning-based reference points and stock status using YPR, SPR, LB-SPR and FISHBLICC analysis, 3) quantify the sensitivity of these estimates to life-history parameter uncertainty, and 4) discuss the implications and limitations of these methods for the assessment and management of data-limited shark stocks in the IOTC region.

2. Material and methods

2.1. Species

The analysis presented here focuses on four pelagic shark species relevant to IOTC, namely, BSH, FAL, OCS and SPL.

The choice of those species was due to the current priority species for the IOTC WPEB during 2026 (FAL, OCS, SPL), to which BSH was added to this list as a case of a data-moderate species where analytical stock assessments are currently carried out (e.g., SS3, JABBA). So here, the priority species were FAL, OCS and SPL, while BSH was mostly used as a comparative approach using those data-limited methods.

2.2. Data

2.2.1. Life history parameters

For the analysis (per-recruit and length-based analyses) we used estimates of several life history and population dynamics aspects that are available from literature, including von Bertalanffy growth parameters (L_{inf} , K , t_0), female maturity ogive parameters (L_{mat50} , L_{mat95}), length-weight relationship coefficients (a , b) and natural mortality (M).

The life history parameters that were compiled and used are presented in **Table 1**, and the length-length and weight-length relationships are presented in **Table 2**. It is noted that not all studies report the same size measurements, so all

estimations were converted to fork length (FL, cm), to make the analysis consistent with the measurement type most used in the IOTC size-frequency dataset.

Natural mortality was derived from empirical equations based on life history parameters. The equations considered were based on *tmax* (Hoenig, 1983; Jensen, 1996; Hewitt and Hoenig, 2005; Then et al., 2015; Dureuil et al., 2021), growth (Jensen, 1996; Then et al., 2015), and growth with temperature-dependency (Pauly, 1980).

Table 1. Life history parameters (von Bertalanffy growth parameters and female maturity ogive parameters) considered in this study, with the respective values, units, study regions and bibliographic sources.

Species	Parameter	Value	Unit	Region	Source
BSH	Linf (asymptotic size)	290.6	FL	SW Indian Ocean	Andrade et al. 2019
	K (growth coefficient)	0.120	yr ⁻¹	SW Indian Ocean	Andrade et al. 2019
	t0 (age at length 0)	-1.5	yr	SW Indian Ocean	Andrade et al. 2019
	Max. observed age	25	yr	SW Indian Ocean	Andrade et al. 2019
	Lmat50 (Size at 50% maturity)	179.3	FL	Indian Ocean	Zhu et al. 2023
FAL	Linf (asymptotic size)	309.8	TL	Arabian Sea	Varghese et al. 2016
	K (growth coefficient)	0.100	yr ⁻¹	Arabian Sea	Varghese et al. 2016
	t0 (age at length 0)	-2.4	yr	Arabian Sea	Varghese et al. 2016
	Max. observed age	19	yr	E Indian Ocean	Hall et al. 2012
	Lmat50 (Size at 50% maturity)	226.5	TL	Arabian Sea	Varghese et al. 2016
OCS	Linf (asymptotic size)	309.4	TL	NW Pacific	Joung et al. 2016
	K (growth coefficient)	0.085	yr ⁻¹	NW Pacific	Joung et al. 2016
	L0 (size at birth)	64	TL	NW Pacific	Joung et al. 2016
	Max. observed age	17	yr	W Central Pacific	D'Alberto et al. 2017
	Lmat50 (Size at 50% maturity)	193.4	TL	NW Pacific	Joung et al. 2016
SPL	Linf (asymptotic size)	233.1	FL	NW Atlantic	Piercy et al. 2007
	K (growth coefficient)	0.09	yr ⁻¹	NW Atlantic	Piercy et al. 2007
	t0 (age at length 0)	-2.2	yr	NW Atlantic	Piercy et al. 2007
	Max. observed age	30	yr	NW Atlantic	Piercy et al. 2007
	Lmat50 (Size at 50% maturity)	219.4	TL	Pacific	Estupiñán-Montaña et al. 2021

Table 2. Length-length and Length-weight relationships considered in this study, with the respective values, units, study regions and bibliographic sources.

Equation	Species	a	b	Units	Region	Source
Fork length from total length: $FL = (a)TL + b$	BSH	0.831	1.391	FL (cm); TL (cm)	NW Atlantic	Kohler et al. 1996
	FAL	0.839	-	FL (cm); TL (cm)	NW Atlantic	Kohler et al. 1996
	SPL	0.776	-	FL (cm); TL (cm)	NW Atlantic	Kohler et al. 1996
	OCS	0.817	-	FL (cm); TL (cm)	Indian Ocean	Joung et al 2016
Total weight from fork length: $WT = (a)FL^b$	BSH	1.59E-05	2.846	WT (Kg); FL (cm)	Indian Ocean	Romanov and Romanova 2009
	FAL	1.60E-05	2.915	WT (Kg); FL (cm)	Indian Ocean	Romanov and Romanova 2009
	SPL	7.77E-06	3.067	WT (Kg); FL (cm)	NW Atlantic	Kohler et al. 1996
	OCS	3.86E-05	2.756	WT (Kg); FL (cm)	Indian Ocean	Romanov and Romanova 2009

2.2.2. Size frequency data

Size-frequency data were obtained from the IOTC size-frequency dataset for sharks (IOTC-DATASETS-2026-02-06-SF-SKH-2005-2024), covering the period 2005–2024. This provides shark size samples by 5 cm fork length (FL) bins, with associated information on year, month, fleet, gear, species and spatial area (1*1 or 5*5).

The available gear codes were grouped into four categories to simplify the overall gear comparisons, using the following categorization:

- Longline: LL, LLOB, FLL, FLLOB, LLCO, ELL, ELLOB, LLEX,
- Purse seine: PS, PSOB, PSS
- Gillnet: GILL, GIOF, G/L
- Other: HAND, RIN, RNOF, TROL, UNCL.

We note that a few records exist with missing gear codes (339 records, <0.1% of the total data) that were excluded from the analyses.

Size filters were applied given the existence of some records with some very small and unrealistic size values, under the size-at-birth for those species. As such, for all species, this minimum bound was set to 40cm FL, with any records lower than this being excluded.

In terms of spatial information, most data is presented in 5*5 degrees but some is presented in 1*1 resolution. To maintain consistency, all spatial information was standardized and recalculated to the 5*5° resolution.

2.3. Analyses

2.3.1. Exploratory data analysis

An initial exploratory data analysis was conducted to characterize and describe the size composition available for each species and gear. This initial exploratory analysis included descriptive plots on: 1) overall size distributions by species and gear, 2) annual size distributions by species and gear, and 3) spatial and temporal distribution patterns by species and gear.

2.3.2. Yield Per Recruit analysis (YPR)

Yield per recruit (YPR) was computed using the Thompson-Bell / Beverton-Holt dynamic pool model (Thompson and Bell, 1934; Beverton and Holt, 1957). We assumed a knife-edge selectivity, meaning that fish become fully recruited to the fishery when they reach the length at first capture (L_c), which is converted to an age at first capture (t_c) from the von Bertalanffy growth equation. The YPR is computed by the following numerical integration:

$$YPR = \int_{t_c}^{t_{max}} F \times N(t) \times W(t) dt$$

Where F is the fishing mortality, $N(t)$ is the survivorship at age t , and $W(t)$ is the weight at age, integrated from the age at first capture (t_c) to the maximum observed age (t_{max}), using a time step of $dt = 0.01$ years.

The survivorship at age is given by:

$$N(t) = e^{-Z(t-t_c)}, \text{ with } Z = M + F$$

Where $N(t)$ is the survivorship at age t relative to t_c under total mortality Z (the sum of natural mortality M and fishing mortality F).

The weight at age ($W(t)$) and length at age ($L(t)$) are given by:

$$W(t) = a \times L(t)^b$$

$$L(t) = L_{\infty} (1 - e^{-K(t-t_0)})$$

Where $W(t)$ is the weight at age t , obtained from the length-weight relationship with coefficients a and b , $L(t)$ is the length at age from the von Bertalanffy growth function, defined by an asymptotic length (L_{∞}), growth coefficient (K), and theoretical age at length zero (t_0).

YPR was evaluated across a range of fishing mortality values ($F = 0$ to 1.0 yr^{-1}) and across a grid of various L_c scenarios for each species (10 cm intervals, between 40-105% of the estimated L_{mat50} , the size at 50% maturity). This produced 11-13 scenarios per species, covering theoretical ranges of selectivity from juvenile to mature fish only catch.

Two reference points were derived from the YPR analysis, namely F_{max} and $F_{0.1}$. F_{max} is the fishing mortality that maximizes yield per recruit, while $F_{0.1}$ is the fishing mortality at which the slope of the YPR curve is 10% of the slope at the origin (Gulland and Boerema, 1973). When compared to F_{max} , $F_{0.1}$ is usually considered a more appropriate reference point for elasmobranchs (Cortés, 2008), and many other fish species in general, since F_{max} is often undefined for species with flat-topped YPR curves, where yield approaches an asymptote and the maximum is achieved at very high and implausible F values.

2.3.3. Spawning Potential Ratio (SPR)

The spawning potential ratio (SPR) was calculated as the ratio of spawning stock biomass per recruit under fishing (SSB/R at $F > 0$) to the unfished spawning stock biomass per recruit (SSB/R at $F = 0$) (Goodyear, 1993):

$$SPR = \frac{(SSB/R)_F}{(SSB/R)_{F=0}}$$

Where $(SSB/R)_F$ is the spawning stock biomass per recruit at fishing mortality F , and $(SSB/R)_{F=0}$ is the spawning stock biomass per recruit at the unfished state when $F=0$.

The spawning stock biomass per recruit integrates from the age at recruitment (t_{rec}) to the maximum age (t_{max}), and is given by:

$$SSB/R = \int_{t_{rec}}^{t_{max}} N(t) \times W(t) \times m(t) dt$$

Where $N(t)$ is the survivorship at age t , $W(t)$ the weight at age t (as defined in the YPR equations), $m(t)$ is the proportion mature at age t , t_{rec} is the age at recruitment and t_{max} is the maximum observed age, and uses a time step of $dt = 0.01$ years.

Fishing mortality was applied to the ages at or above t_c (the age corresponding to L_c , from the von Bertalanffy growth equations), while younger fish contribute to spawning biomass considering only their natural mortality rate. The reproductive output at each age (length class) was calculated by a logistic maturity ogive:

$$m(L) = \frac{1}{(1 + e^{-\ln(19)(L - L_{mat50}) / (L_{mat95} - L_{mat50})})}$$

Where $m(L)$ is the proportion mature at length L , evaluated at length-at-age predicted by the von Bertalanffy growth curve, L_{mat50} and L_{mat95} are the lengths at 50% and 95% maturity, respectively. Note that L_{mat95} was approximated as $L_{mat50} + 25$ cm for species where there were no published ogive slope parameters.

SPR was evaluated across the same F range and L_c grid as the YPR analysis. Two biological reference points were calculated, namely F_{SPR40} and F_{SPR20} . Specifically, F_{SPR40} , is the fishing mortality that reduces SPR to 40% of its unfished value and is often considered a precautionary target for fish populations like elasmobranchs, while F_{SPR20} is the F that reduces SPR to 20% and is often considered a limit reference point, especially for vulnerable species like elasmobranchs (Brooks et al., 2010).

To consider life-history parameter uncertainty through the SPR reference points, a Monte Carlo analysis was conducted. For each species, 2000 parameter sets were drawn from the following distributions: $L_{inf} \sim \text{Normal}$ (CV = 5%), $K \sim \text{Normal}$ (CV = 15%), $L_{mat50} \sim \text{Normal}$ (CV = 10%), and $M \sim \text{Uniform}$ (bounded by the minimum and maximum across the eight empirical estimators). The parameters t_0 , t_{max} , and length-weight coefficients were held fixed, and draws were constrained to biologically plausible combinations (i.e., only when $L_{mat50} < L_{inf}$).

2.3.4. Length-Based Spawning Potential Ratio (LB-SPR)

The length-based spawning potential ratio (LB-SPR) method developed by Hordyk et al. (2015, 2016) was used to estimate SPR from the observed size-frequency data. This data-limited assessment method fits a model to the length composition that jointly estimates the selectivity parameters (SL_{50} and SL_{95} , the lengths at 50% and 95% selectivity)

and the ratio F/M , from which SPR is derived. The model assumes equilibrium conditions, logistic (asymptotic) selectivity, and that the sampled length composition is representative of the exploited population.

The LB-SPR model uses several biological inputs, namely the asymptotic length (L_{inf}) from the von Bertalanffy growth equation, the ratio of natural mortality to the growth coefficient (M/K), and the values from the maturity ogive (L_{mat50} and L_{mat95}).

Based on the exploratory analysis of the data, the LB-SPR models were applied to three species/gear combinations for which there was more data available, namely blue shark longline (BSH-LL), silky shark longline (FAL-LL), and silky shark purse seine (FAL-PS). Oceanic whitetip and scalloped hammerhead were not assessed with LB-SPR due to insufficient sample sizes.

The sensitivity of LB-SPR estimates to uncertain biological inputs was assessed by refitting the model across a grid of M/K and L_{inf} values. The M/K ratio was varied across five values spanning the range derived from the empirical mortality estimators, and L_{inf} across five values spanning $\pm 10\%$ of the point estimate, giving 25 parameter combinations per species/gear combination. This analysis produced, for each species and gear, a median annual SPR trajectory with a respective uncertainty envelope.

Current absolute fishing mortality was estimated for each species/gear by multiplying the LB-SPR median F/M ratio by the median M from the empirical estimators. Years where the model did not converge were excluded from this calculation. The resulting current F estimates were compared against the corresponding species/gear-specific stochastic reference point distributions calculated by the SPR analysis, to derive the probability of current F exceeding the SPR 40% target and SPR 20% limit reference points. This probability was calculated as the proportion of Monte Carlo iterations in which the estimated current F exceeded the corresponding reference points.

2.3.5. Bayesian Length Interval Catch Curve Analysis (FISHBLICC)

To complement the LB-SPR application, we applied FISHBLICC (Bayesian Length Interval Catch Curve Analysis), a recently developed method for data-limited fisheries stock assessments (Medley, 2025). This was applied to the same length frequency dataset for blue shark and silky shark, specifically, the “Longline” fishery data for blue shark, and the “Longline” and “Purse Seine” fishery data for silky shark.

Like the LB-SPR approach, FISHBLICC utilizes length frequency data from fishery catch samples to estimate key parameters such as fishing mortality and spawning potential ratio (SPR), providing a measure of stock depletion relative to the unfished level (SPR₀). However, FISHBLICC provides greater flexibility than LB-SPR by accommodating both asymptotic (logistic) and dome-shaped selectivity patterns (e.g., double normal selection curves with ascending and descending limbs). This allows for more realistic modeling of fisheries that caught younger, smaller fish, such as the purse seine fishery. Additionally, FISHBLICC can simultaneously fit length frequency data from multiple fisheries, each with its own selectivity pattern, thereby improving the precision of selectivity and fishing mortality estimates for individual fisheries.

FISHBLICC, like LB-SPR, relies on the critical assumption that length frequency data are collected under equilibrium conditions, with no recruitment variability. While life-history parameters (such as the M/K ratio, growth, and maturity) are treated as fixed model inputs, FISHBLICC accounts for uncertainty in fish growth by integrating survivorship over a distribution of L_{∞} , assumed to follow a Gamma distribution with an estimable coefficient of variation. The model is also implemented using full Bayesian estimation via the RSTAN package, providing robust quantification of parameter uncertainty.

For blue shark, one model was implemented for the Longline length frequency data from 2009-2024, assuming a logistic selectivity. Each annual length frequency is fitted independently, with parameters estimated for each year (including selectivity). The following biological parameters are used as input, based on values used in the LB-SPR analysis:

- $L_{\infty} = 290.6$ cm ($\sigma_{(L^{\infty})}=10$)
- $M/K = 1.45$ (the ratio of natural mortality M to growth rate K)
- $L_{50} = 179.3$ cm (length at 50% maturity)
- $L_{95} = L_{50} + 25$ cm (length at 95% maturity)
- $a = 1.59E-05$, $b = 2.541$ (length weight relationship)

For silky shark, two models were implemented for length-frequency data (2013–2024) from the longline and purse seine fisheries. The first model assumed logistic selectivity for the longline fishery and double-normal selectivity for the purse seine fishery. The second assumed double-normal selectivity for both. In each year, longline and purse seine data were fitted simultaneously, with weightings of 0.6 and 0.4 respectively, loosely based on relative catch. These weightings determine the relative fishing mortality attributed to each fishery.

The assumption of dome-shaped selectivity for the purse seine fishery is justified given the much smaller fish caught in that fishery. However, uncertainty remains around longline selectivity: silky shark has a high L_{∞} , yet large individuals (e.g., >200 cm) appear in lower proportions than in blue shark catches. This uncertainty is captured by the alternative model, which relaxes the asymptotic selectivity assumption for the longline fishery. The following biological parameters are used as input:

- $L_{\infty} = 309.8$ cm ($\sigma_{(L^{\infty})}=10$)
- $M/K = 2.11$ (the ratio of natural mortality M to growth rate K)
- $L_{50} = 226.5$ cm (length at 50% maturity)
- $L_{95} = L_{50} + 25$ cm (length at 95% maturity)
- $a = 1.60E-05$, $b = 2.915$ (length weight relationship)

2.4. Software

All analysis was carried out using R 4.5.1 (R Core Team, 2025), with the use of several additional packages, namely: “tidyverse” (Wickham et al., 2019), “readxl” (Wickham and Bryan, 2025), “viridis” (Garnier et al., 2024), “openxlsx” (Schauberger and Walker, 2025), “sf” (Pebesma, 2018; Pebesma and Bivand, 2023), “rnatuarearth” (Massicotte and South, 2025), “patchwork” (Pedersen, 2025). The length-based SPR assessment model used the package “LBSPR” (Hordyk, 2021). FISHBLICC is available from <https://github.com/PaulAHMedley/fishblicc> (Medley, 2026).

3. Results

3.1. Exploratory data analysis

3.1.1. Size distribution data

The species-specific sample sizes were approximately 316,000 samples for BSH, 44,000 for FAL, 639 for OCS, and 262 for SPL. The overall size distribution of those four shark species is presented in **Figure 1**.

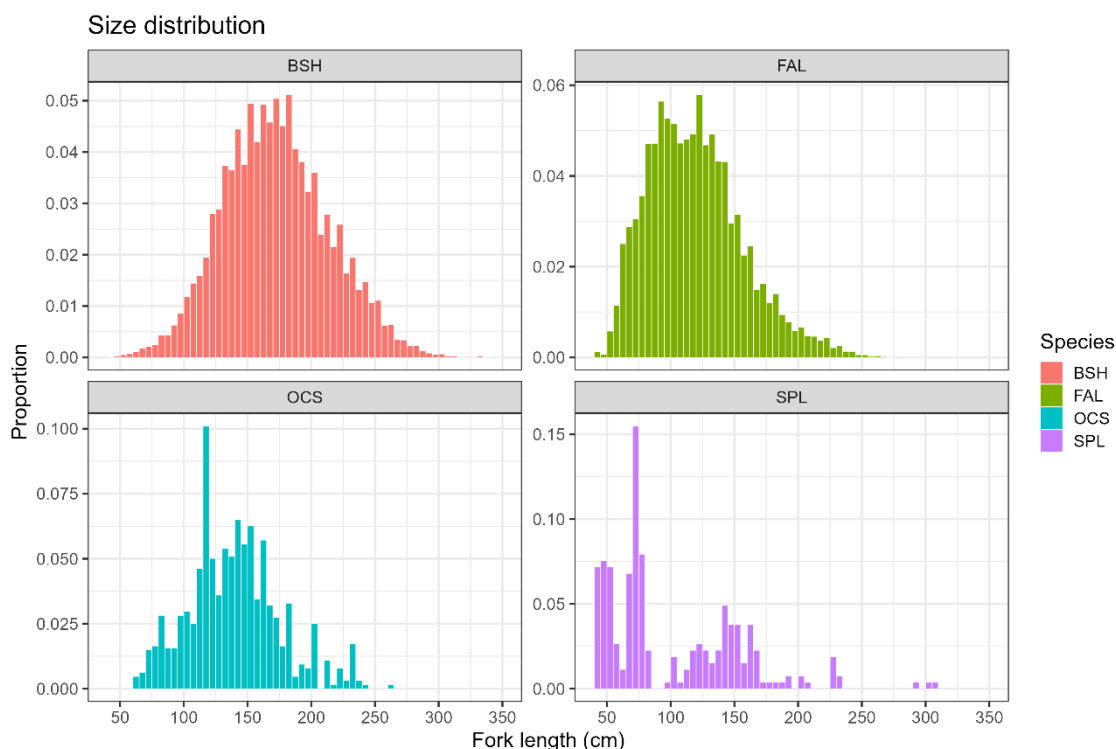


Figure 1. Size distribution for the pelagic shark species focused on this study for the Indian Ocean (IOTC). All years and gears are pooled, the sizes are represented in fork length (FL, cm) in 5cm size class bins.

3.1.2. Gear related patterns

The size data contains a mix of several years and fishing gears, which can be seen in **Figure 2**.

The BSH was mostly sampled by longline (~93%), with minor contributions from gillnet and other gears. In this species, the longline size sampling was consistent across the time series, with annual samples exceeding 2,000 fish from 2008 onward and peaking above 30,000 fish in some years.

The FAL showed an overall more balanced size composition contribution, with longline contributing approximately 58% of the data and purse seine 33%. However, in this species the gear composition shifted substantially over time, with longline gear dominant throughout most of the time series, while the purse seine coverage increased markedly from the 2020 onwards.

The OCS had much less sizes sampled and was predominantly sampled by longlines (~65%), and purse seine (~30%). Longlines have a more consistent sampling over time but with some gaps, while the purse seine data increased since 2020 for this species.

Finally, the SPL had much less samples available and was mostly sampled by gillnets (~79%), with some occasional contributions from longlines and other gears.

In terms of gear specific size distribution, for BSH it is noted that there is a relatively large overlap of the sizes in each gear, while for FAL there is a clearer distinction with purse seine sampling smaller sharks and longlines and gillnets larger animals. For OCS the size distribution is much overlapped for purse seines and longlines, while for SPL there is a clear distinction in gears, with gillnets capturing smaller sharks and longlines larger ones (**Figure 3**).

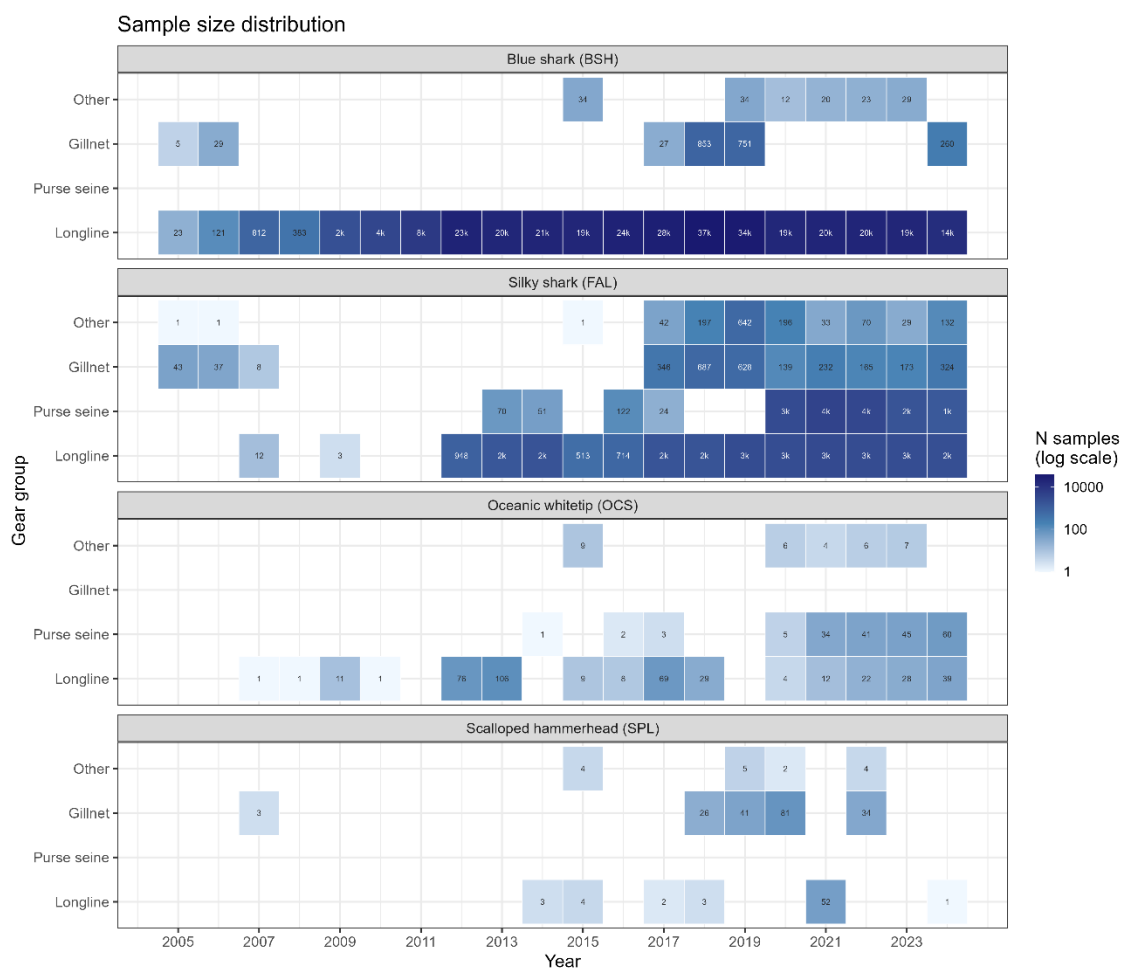


Figure 2: Number of size samples per year and fishing gear for the IOTC shark species focused on this study. The cells are labelled with the sample counts (k = thousands) and empty cells represent no data for those species/gear/year combinations.

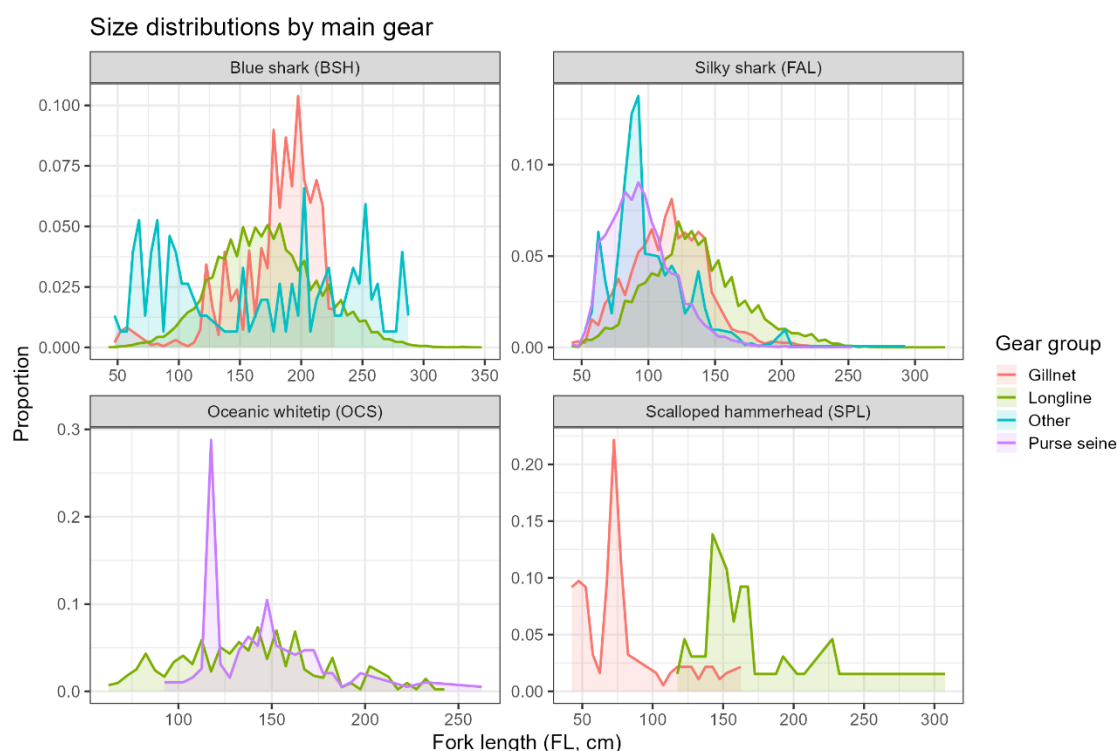


Figure 3: Size distribution by fishing gear group for the pelagic shark species focused on this study for the Indian Ocean (IOTC). All years and gears are pooled, the sizes are represented in fork length (FL, cm) in 5cm size class bins.

3.1.3. Spatial distribution

It is interesting to note the spatial distribution of the size data across the various species, that is represented in **Figure 4**. The BSH size records are spread and cover most of the IOTC wide area including the tropical and temperate regions, while FAL tends to cover mostly the tropical regions but also the temperate region of the SW Indian Ocean. The OCS records come mostly from the western Indian Ocean, and the SPL records are much more sporadic and occasional.

In terms of spatial size distribution, BSH shows patterns with larger sizes in the tropical areas and smaller in the temperate regions, while FAL shows some differences with smaller specimens in the more tropical regions and slightly larger mean sizes in the temperate SW area (**Figure 5**).

Finally, it is also interesting to note the spatial distribution of the fishing gears that capture and sample those species in each area, which is represented in **Figure 6**. BSH is mostly sampled by longline on all the Indian Ocean area with some gillnets in the tropical north area, while for FAL it is possible to see a gradient, with purse seines sampling mostly in the tropical NW area, longlines in the remaining areas and some more local gillnets. For OCS and SPL there are also some spatial patterns, but less distinguishable given that size sampling is much more limited.

Spatial distribution of the size samples

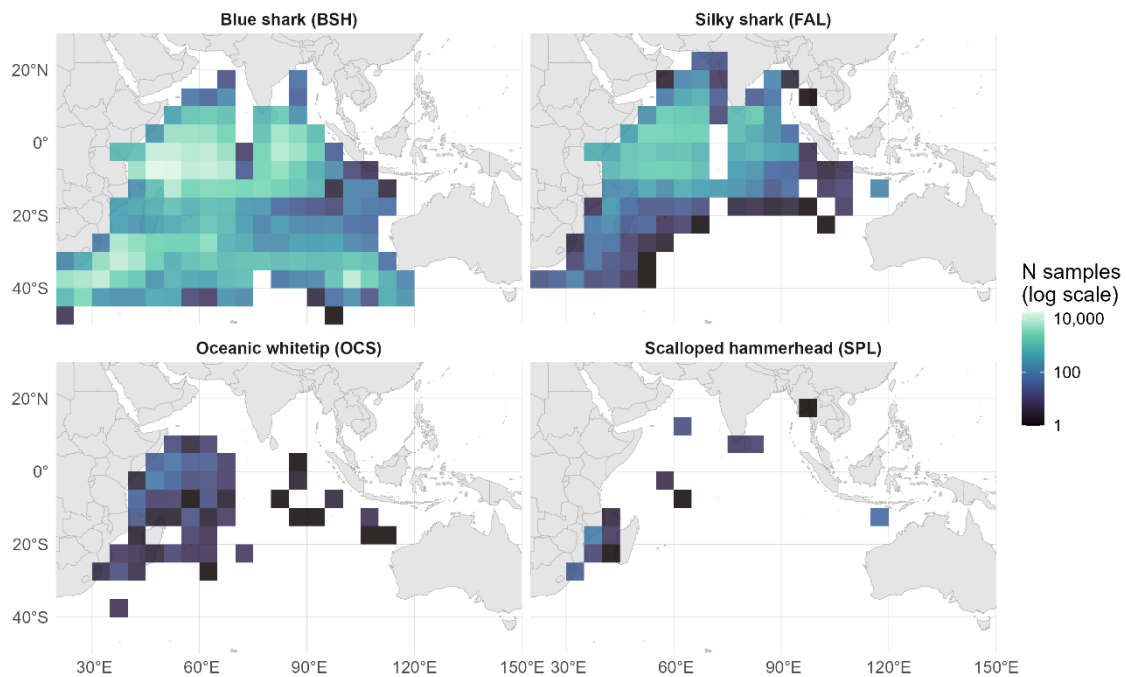


Figure 4. Maps with the sample size distribution (N samples) of the IOTC shark species focused in this study. The N samples available are calculated per 5° × 5° cell, for all years and gears pooled together.

Spatial distribution of the mean sizes

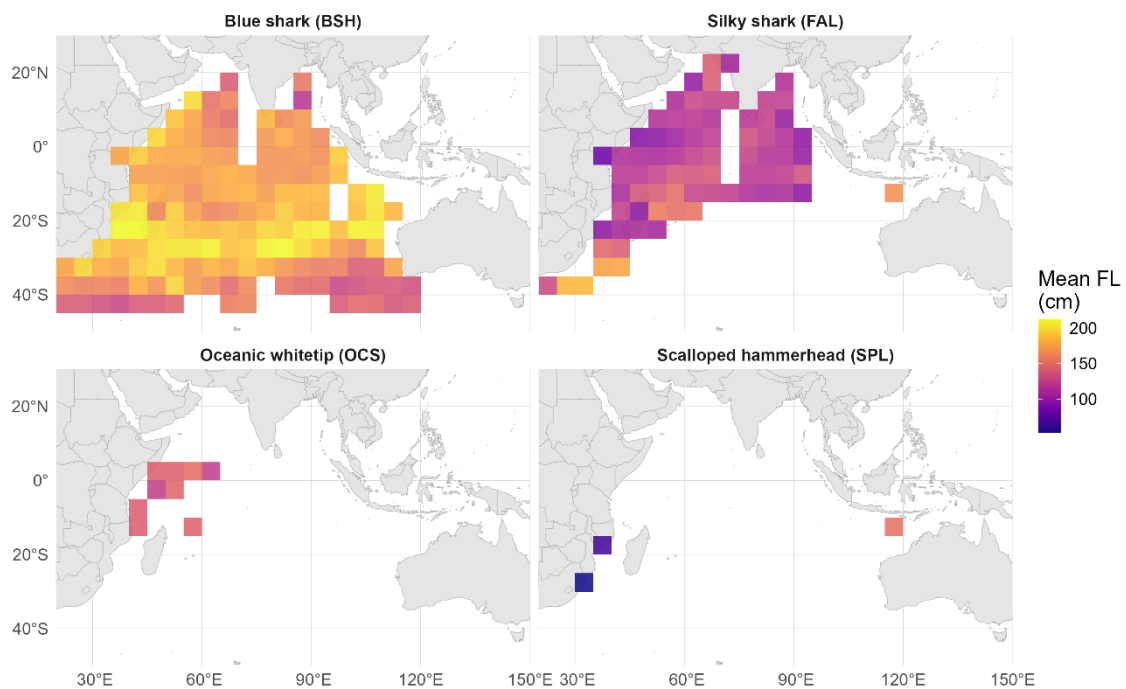


Figure 5. Maps with the mean size (FL, cm) of the IOTC shark species focused in this study. The mean sizes are calculated per 5 × 5 cell, for all years and gears pooled together. Only 5x5 spatial cells with ≥ 20 size samples are represented in the maps.

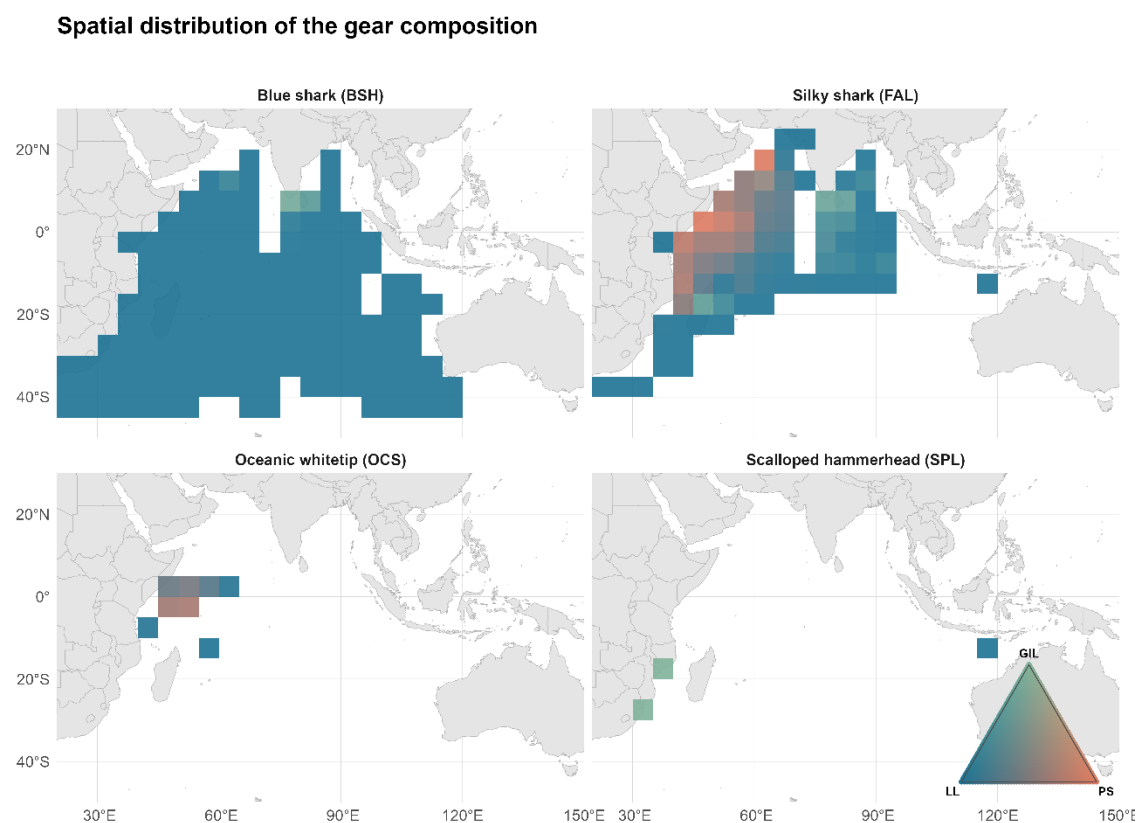


Figure 6. Maps with the gear composition of size samples available for the IOTC shark species focused on this study. The gear composition is calculated for the 3 main gears (longline, purse seine and gillnet) per 5 × 5 cell, for all years and gears pooled together. Only 5x5 spatial cells with ≥ 20 size samples are represented in the maps.

3.1.4. Temporal patterns

There were temporal size distributions patterns visible over the years for the main species where there is sufficient data to make an annual analysis, namely BSH and FAL (**Figure 7**). For FAL there is an overall reduction in the mean sizes over time, that can in part be explained by the fact that from 2020 onwards there was the addition of a significant amount of PS data that is composed of smaller sized specimens, even though looking only to the longline data there is also a reduction in mean sizes. For BSH most of the data comes from longline, and in this case there is an increase from the initial years until 2011, followed by a more stable period until 2019, and then a downward trend with oscillations in the more recent years.

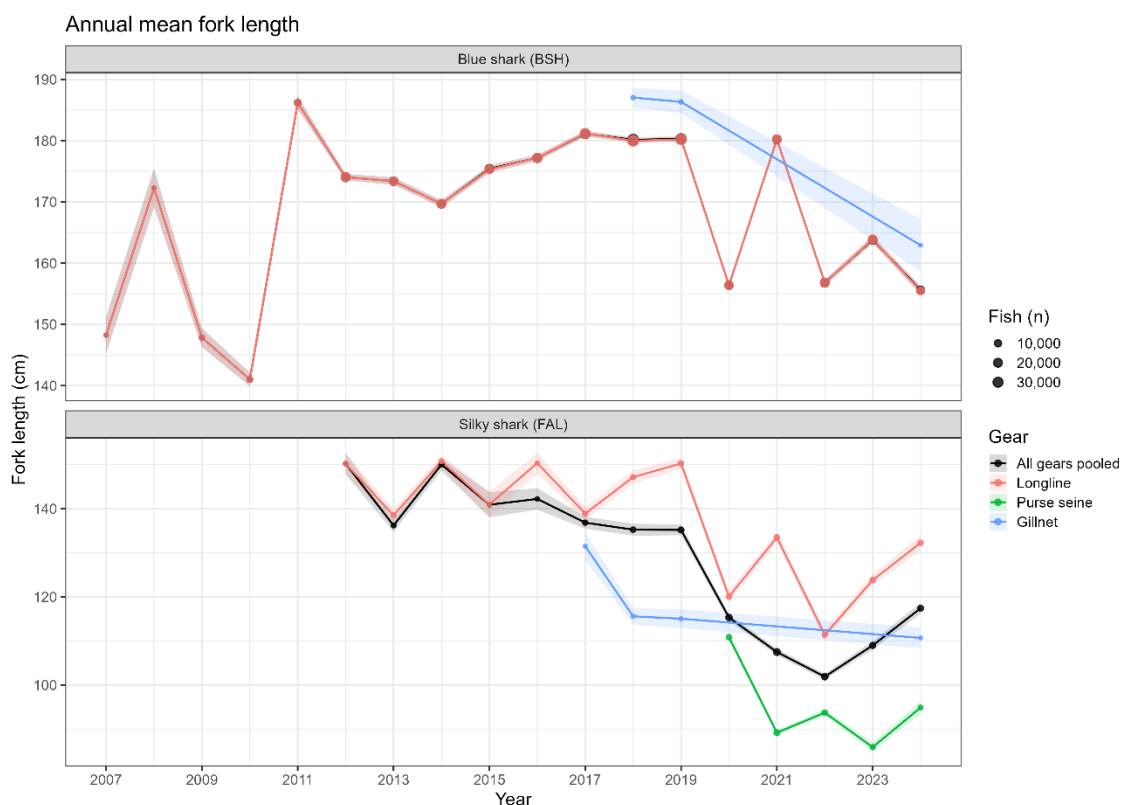


Figure 7. Time series of mean size (FL, cm) for BSH and FAL, for each gear separately and for all gears combined. The bands represent the 95% CIs. Only gear/year combinations with ≥ 250 size samples are represented.

3.2. Estimations of M and M/K from biological data

The range of M estimates across the various empirical methods used are presented in **Figure 8**. The details of the estimated M values, as well as the related M/K values are presented in **Table 3**.

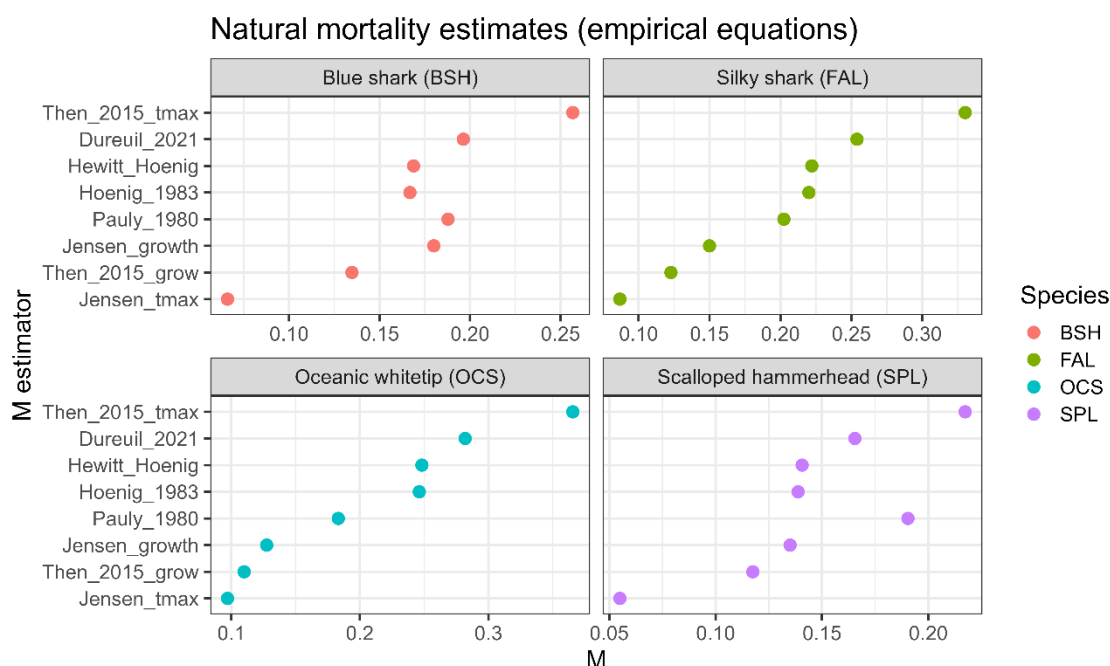


Figure 8. Values of natural mortality (M) derived from the life history parameters and the various empirical equations used.

Table 3. Values of natural mortality (M) and M/K derived from the life history parameters and various empirical equations used. The values are presented for each estimator, as well as the median, min and max from the various estimators.

Estimator	BSH		FAL		OCS		SPL	
	M	M/K	M	M/K	M	M/K	M	M/K
Hoenig_1983	0.167	1.39	0.220	2.20	0.246	2.90	0.139	1.54
Then_2015_tmax	0.257	2.14	0.330	3.30	0.366	4.30	0.217	2.41
Then_2015_grow	0.135	1.12	0.123	1.23	0.110	1.29	0.118	1.31
Jensen_tmax	0.066	0.55	0.087	0.87	0.097	1.14	0.055	0.61
Jensen_growth	0.180	1.50	0.150	1.50	0.128	1.50	0.135	1.50
Pauly_1980	0.188	1.57	0.202	2.02	0.183	2.16	0.190	2.12
Hewitt_Hoenig	0.169	1.41	0.222	2.22	0.248	2.92	0.141	1.56
Dureuil_2021	0.196	1.64	0.254	2.54	0.282	3.32	0.166	1.84
Minimum	0.066	0.55	0.087	0.87	0.097	1.14	0.055	0.61
Median	0.174	1.45	0.211	2.11	0.215	2.53	0.140	1.55
Maximum	0.257	2.14	0.330	3.30	0.366	4.30	0.217	2.41

3.3. Yield Per Recruit analysis (YPR)

Yield-per-recruit curves showed the characteristic pattern of increasing yield with fishing mortality for all four species, with the shape of the curve and the maximum attainable yield strongly dependent on the length at first capture (**Figure 9**).

For the lowest L_c scenarios, the YPR curves were dome-shaped, with a clearly defined maximum (F_{max}) beyond which yield declined due to growth overfishing, where fish are removed before realizing their full growth potential. As L_c increased, the curves became increasingly flat-topped, and F_{max} shifted to progressively higher (and often unrealistic) values of F , highlighting that F_{max} is an uninformative and often unrealistic reference point for these species.

With regard to $F_{0.1}$, this reference point increased with L_c for all species, reflecting the greater fishing pressure that can be sustained when mostly larger individuals are harvested. For BSH, yield per recruit at $F_{0.1}$ ranged from approximately 10 kg at the smallest L_c (~70 cm) to 40 kg at the largest L_c (~190 cm). The same pattern was evident for silky shark (~7 to ~54 kg at $F_{0.1}$), oceanic whitetip, and scalloped hammerhead, where harvesting larger individuals yielded considerably more biomass per recruit than harvesting juveniles.

At a selectivity that is in general representative for those species (e.g., $L_c \sim 120$ – 130 cm), $F_{0.1}$ was estimated at 0.150 – 0.165 yr^{-1} for blue shark, 0.225 – 0.245 yr^{-1} for silky shark, 0.275 – 0.305 yr^{-1} for oceanic whitetip, and 0.145 – 0.160 yr^{-1} for scalloped hammerhead.

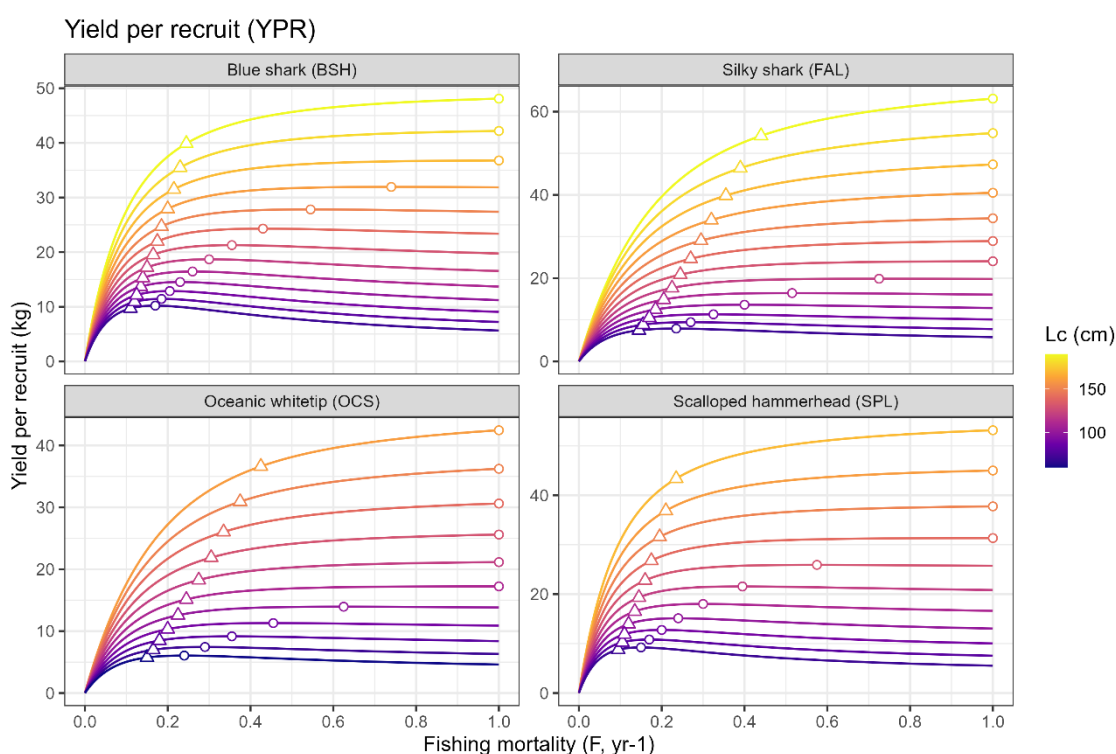


Figure 9. Yield per recruit analysis for IOTC shark species focused on this study. The circles in the lines represent F_{max} , and the triangles represent $F_{0.1}$.

3.4. Spawning Potential Ratio (SPR)

The SPR declined with increasing fishing mortality for all species and selectivity (L_c) scenarios (**Figure 10**). At low L_c (i.e., fishery catching juveniles) SPR decreases rapidly, crossing both SPR 40% and SPR 20% reference points even at relatively low F values. At high L_c (i.e., fishery catching only late juveniles or adults) the SPR decline is more gradual, and in some cases the curves remained above the limit reference point across the entire range of F values that were evaluated.

Considering a selectivity (L_c) that is in general representative for those species (~ 120 – 130 cm FL), F at SPR40% was estimated at 0.102 – 0.108 yr^{-1} for BHS, 0.098 – 0.108 yr^{-1} for FAL, 0.143 – 0.170 yr^{-1} for OCS and 0.078 – 0.086 yr^{-1} for SPL. The SPL showed the lowest F_{SPR40} values.

It is noted that when comparing reference points based on YPR (i.e., $F_{0.1}$) with SPR (F_{SPR40}), the $F_{0.1}$ values exceeded F_{SPR40} for most cases and scenarios. This means that fishing those species at $F_{0.1}$ (the yield-optimizing reference point) would in most cases risk driving the spawning potential below the 40% target, in some cases even approaching the SPR 20% limit. This divergence was greatest for FAL and OCS, indicating that yield-based reference points seem to be particularly non-precautionary for these shark species.

The isopleth diagrams summarize the possible management trade-offs between reducing fishing mortality and increasing the size at first capture, in order to maintain the stocks at the target SPR40% reference points (**Figure 11**). For all species, the SPR reference points, including SPR40%, moved upwards very steeply, indicating that maintaining this target reference point at higher fishing mortality, requires larger length at first capture. For all species, there is a relatively narrow interval of F/L_c combinations that would sustain the populations at the SPR40% target values.

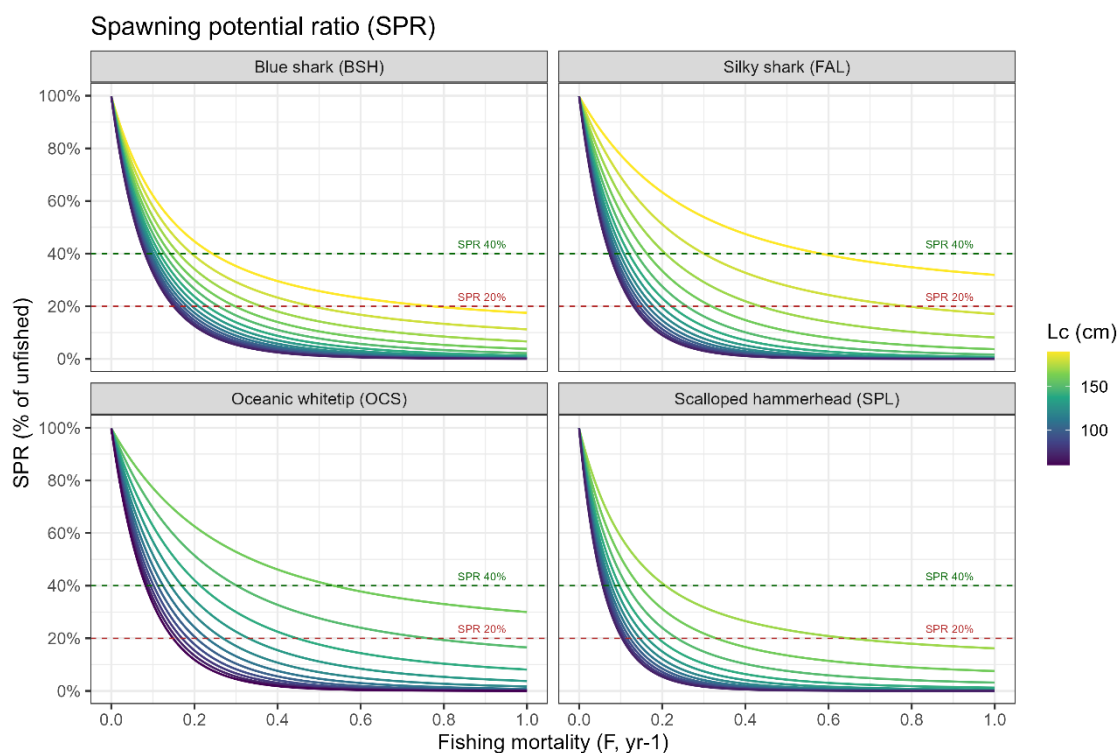


Figure 10. Spawning Potential Ratio (SPR) per recruit analysis for IOTC shark species focused on this study. The green dashed line represents SPR 40% (proxy for target) and the red dashed line represents SPR 20% (proxy for limit).

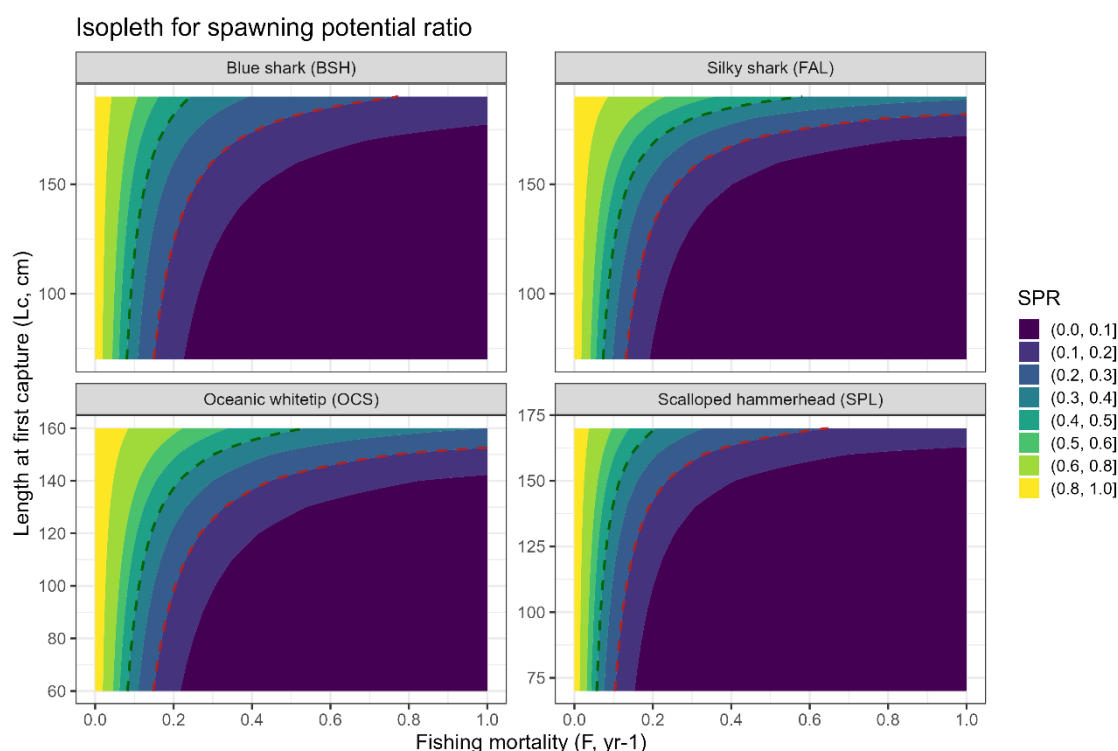


Figure 11. Isopleth lines for Spawning Potential Ratio (SPR) per recruit for the IOTC shark species focused on this study. The green dashed line represents the contour along SPR 40% (proxy for target) and the red dashed line represents the contour along SPR 20% (proxy for limit).

3.5. Length-Based Spawning Potential Ratio (LB-SPR) data-limited assessment

3.5.1. Size selectivity

The length at 50% selectivity (SL_{50}) estimated by the LB-SPR model is shown in **Figure 12**. For FAL, the longline selectivity tended to be higher than for purse seine, with median SL_{50} ~115 cm FL for longline and ~75 cm FL for purse seine. The BSH longline selectivity was higher, with median SL_{50} ~ 130 cm FL. The FAL longline series showed a consistently declining SL_{50} trend in the most recent years, which can indicate a shift toward the capture of smaller individuals. This also needs to be considered when interpreting the corresponding SPR estimates under the LB-SPR model equilibrium assumptions. We also note that BSH shows a very high estimate for one particular year (2011, SL_{50} ~ 230 cm FL), which is likely an artifact due to limited data and unusual size data for that particular year.

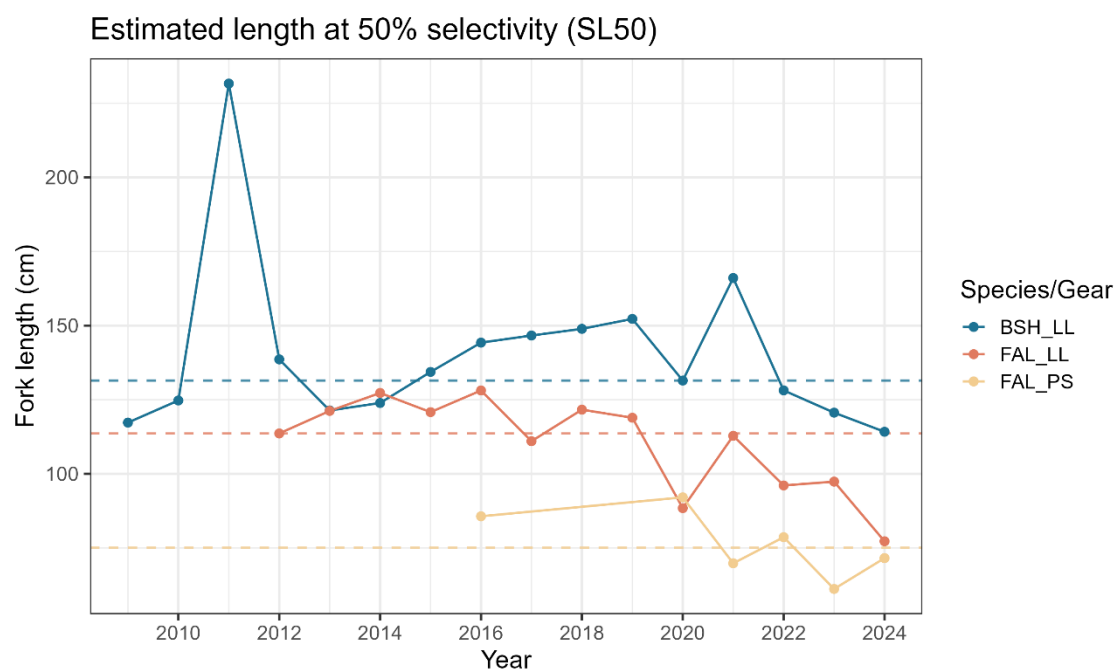


Figure 12. Estimated

length at 50% selectivity (SL50) estimated from the LB-SPR model over the years for when data is available. The dashed lines represent the median SL50 across years in each time series.

3.5.2. LB-SPR

The annual SPR estimates derived from the LB-SPR analysis are shown in **Figure 13**. For BSH, the median SPR fluctuated between approximately 10% and 40% over the time series, and in most years was calculated to be between the limit (SPR 20%) and target (40%) reference points. It is noted that the most recent years (2020–2024) showed median estimates that are generally very close the limit reference point.

The FAL series for longline showed a median SPR fluctuating around the SPR 20% limit for most years, and with slightly lower values in the more recent years. It is noted that that series shows very high SPR estimates in two particular years (2012 and 2024), with very wide uncertainty bands, which are due to limited and atypical size sampling in those years, meaning those particular years should be interpreted with caution. The FAL purse seine series was the most different when compared to the longline series, with median SPR consistently at very low values under the SPR20% limit, which is a likely direct consequence of the fishery impacting mostly juveniles below the size at first maturity.

The current F estimated from the LB-SPR model was compared against the distributions of F_{SPR40} and F_{SPR20} derived from the stochastic per-recruit analysis (**Figure 14**). For BSH, current F (0.148 yr^{-1}) is most likely located between the target and limit reference points, specifically exceeding the target reference point with high probability (96%) but the limit reference point with low probability (5%). For FAL longline, current F (0.150 yr^{-1}) exceeds the target reference with high probability (99%) and the limit with moderate probability (28%). For FAL purse seine, the current F (0.529 yr^{-1}) exceeds both reference points with very high values ($\sim 100\%$).

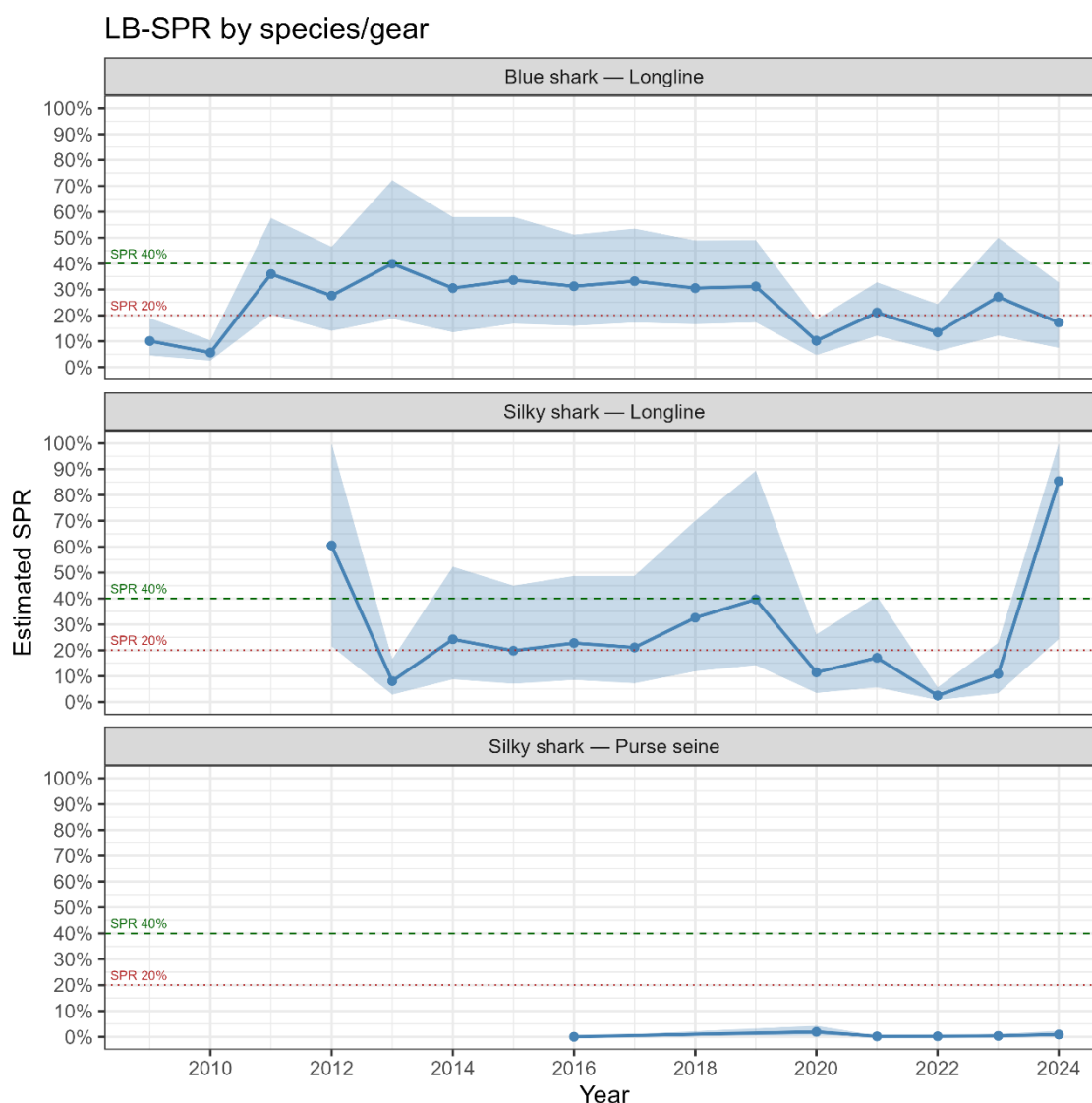


Figure 13. Annual spawning potential ratio (SPR) estimated from the LB-SPR model for the various IOTC species/gears analysed. The solid line represents the median SPR and the blue band the interquartile range across a grid of parameter combinations spanning biological uncertainties. The green dashed line indicates the SPR 40% (target reference point) and the red dotted line the SPR 20% (limit reference point).

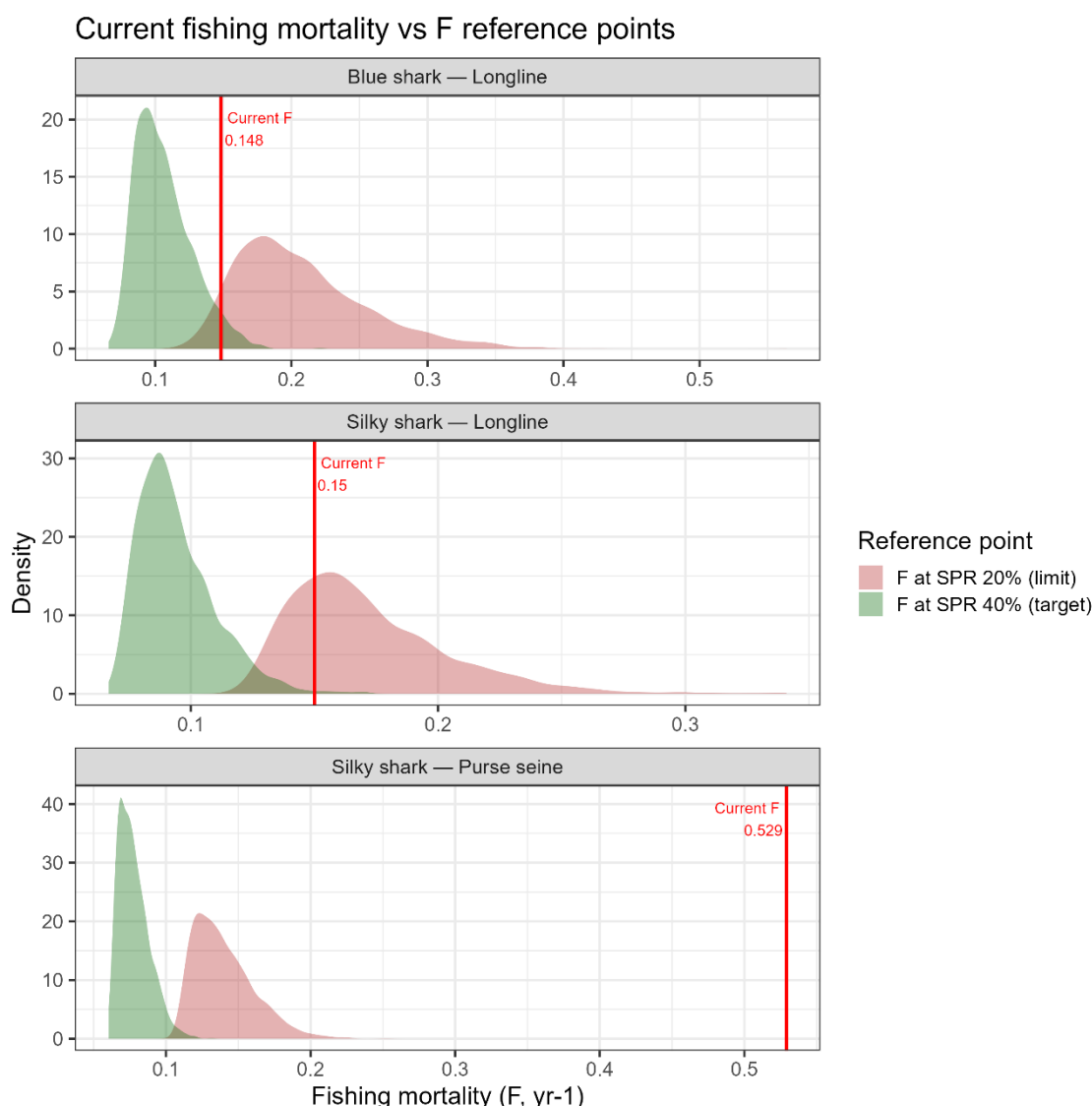


Figure 14. Current fishing mortality (F) estimated from the LB-SPR model compared to the distributions of F reference points derived from the stochastic per-recruit analysis, for the various IOTC species/gear combinations. The density curves show the distributions of F at the SPR 40% target (green) and SPR 20% limit (red) reference points. The vertical red line indicates the current F estimated by the LB-SPR model (median across years).

3.6. FISHBLICC data-limited assessment

For blue shark, the model outcomes are presented in **Figure 15**. The logistic selectivity parameter L50 (length at 50% of full selection) fluctuates around 140 cm over the 2009–2024 period. The notably high value in 2011 is driven by a larger proportion of big fish in the samples, while selectivity shifted towards smaller fish from 2021–2024. Despite these patterns, selectivity estimates are generally stable throughout the period, and the variation more likely reflects sampling variability than a real change in selection.

Across the time period, estimated SPR shows no clear trend. With the exception of an unusually high value in 2013, SPR estimates for all other years fall below the SPR 40% reference point. Values for the most recent five years (2020–

2024) are slightly lower than those from the earlier period. These patterns are broadly consistent with estimates from the LBSPR analysis.

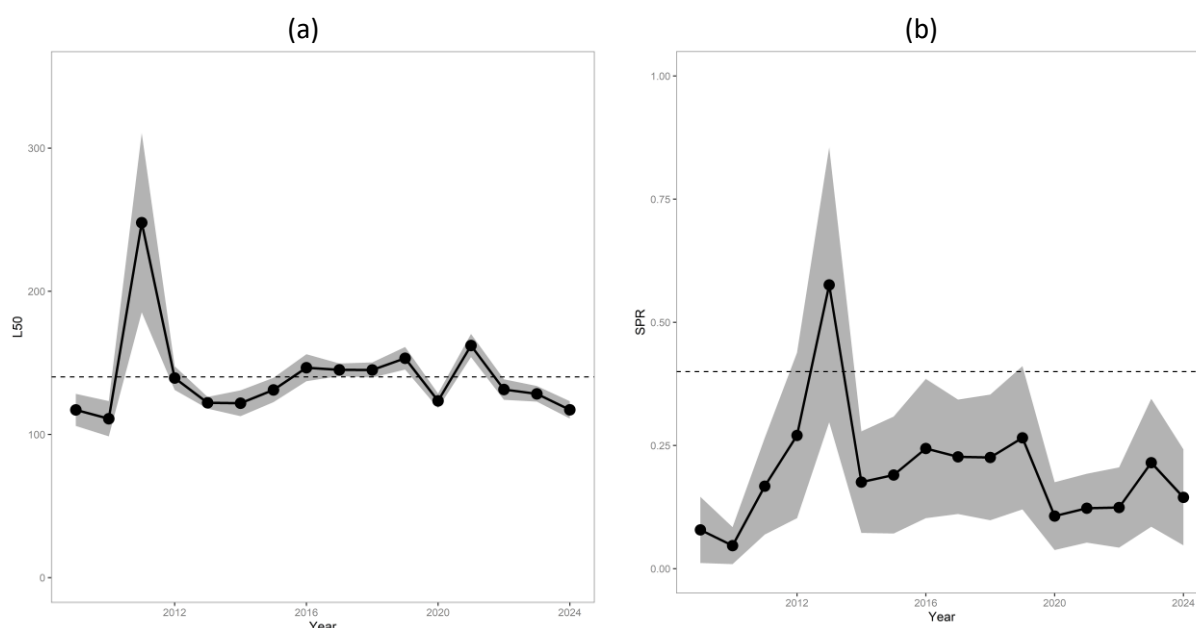


Figure 15. Outputs of the FISHBLICC analysis for blue shark 2011-2024 length frequencies from the Longline fishery: (a) Estimated selectivity parameter L50 (length at 50% selection) for each year (dashed line is the mean of the series (~140cm); (b) estimates of SPR for each year (the dot represents the mode of the posterior Density estimate the shaded areas represents 95% confidence error (dashed line indicates the reference target level of SPR40%).

For silky shark, the model outcomes are presented in **Figure 16** and **Figure 17**. The model is fitted to length frequencies from multiple fisheries simultaneously. The SPR therefore reflects an average fishing mortality that accounts for the mortality rate and selection pattern of both the longline and purse seine fisheries, weighted by their relative catches.

Under the assumption of asymptotic (logistic) selectivity, estimated SPR is very low (less than 5%) throughout the time series, except for 2024 (**Figure 16**). This is driven by the presence of very small fish in the purse seine catch (despite highly dome-shaped selectivity estimates) combined with the lack of larger fish (e.g., >200 cm) relative to L_{∞} (~310 cm) in the longline fishery. When selectivity for the longline fishery is also assumed to be dome-shaped, estimated SPR is substantially higher (>25%; **Figure 17**).

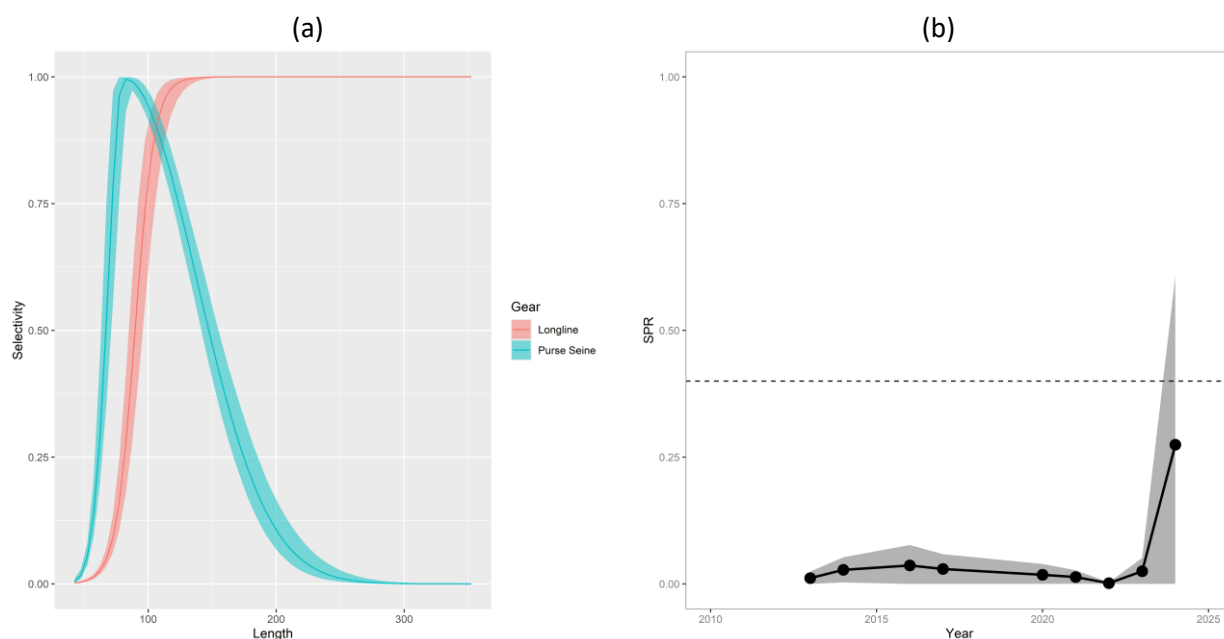


Figure 16. Outputs of the FISHBLICC analysis for silky shark 2013-2024 length frequencies from the Longline and Purse seine fisheries: (a) Estimated selectivity curve in 2024 (logistic selectivity function for the Longline and a double normal selectivity function for the Purse seine); (b) estimates of SPR for each year (the dot represents the mode of the posterior Density estimate; the shaded areas represents 95% confidence error; dashed line indicates the reference level of SPR40%)

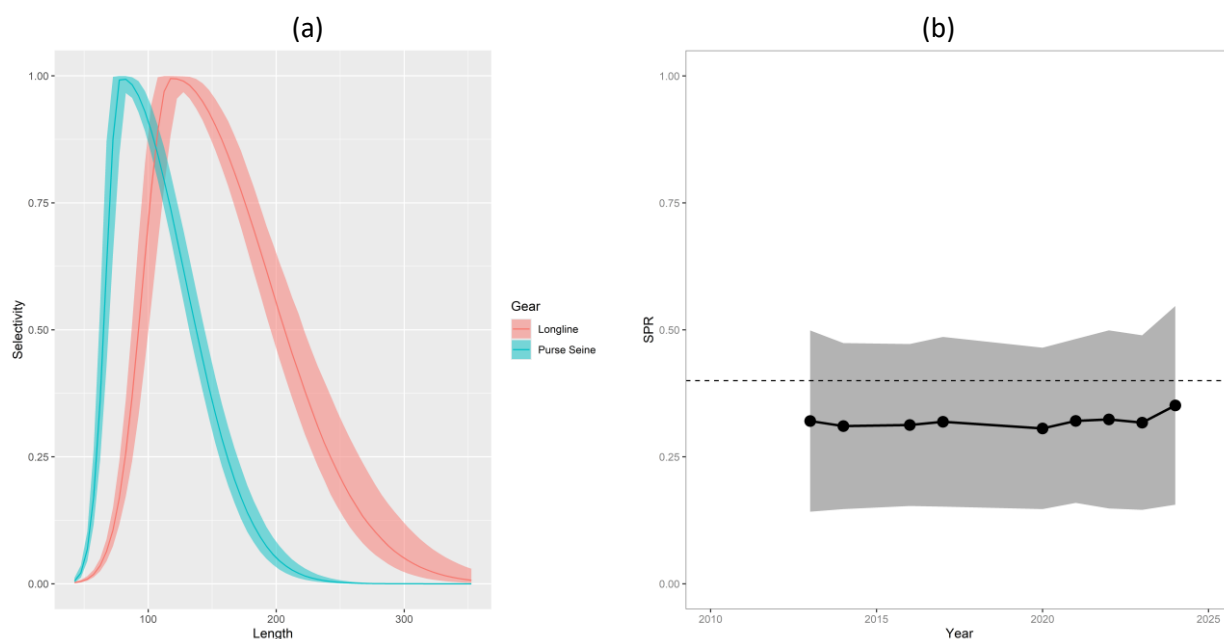


Figure 17. Outputs of the FISHBLICC analysis for silky shark 2013-2024 length frequencies from the Longline and Purse seine fisheries: (a) Estimated selectivity curve in 2024 (double normal selectivity function for both Longline and Purse seine); (b) estimates of SPR for each year (the dot represents the mode of the posterior Density estimate; the shaded areas represents 95% confidence error; dashed line indicates the reference level of SPR40%).

4. Discussion

This study applied a set of data-limited assessment methods to four pelagic shark species in the Indian Ocean, using size-composition data from the IOTC database together with life-history parameters.

A consistent result across all four species is that the yield-based reference point $F_{0.1}$ exceeded the spawning-based target F_{SPR40} in almost all selectivity scenarios. This means that for those species, fishing at the level that maximizes yield per recruit would, in most cases, reduce spawning potential to below the 40% target, generally considered a precautionary reference target for elasmobranchs. This highlights that yield-based reference points are not necessarily precautionary for low-productivity species such as sharks and that spawning-based reference points might be more appropriate for those species.

The length-based results suggested differences in status among the assessed species/gear combinations. For BSH longline, current fishing mortality appears to be above the target but below the limit reference point. For FAL longline, current fishing mortality appears to be above the target, and close of also exceeding the limit reference point. For FAL purse seine, the spawning potential was estimated at very low levels throughout the time series, reflecting the capture of predominantly juvenile individuals well below the size at maturity with this gear, meaning that current fishing mortality is well above both target and limit reference points.

In terms of recommended management actions, for BSH the results should be interpreted alongside the IOTC integrated SS3 stock assessments (Rice, 2025), which estimated the stock to be above the biomass target and below the fishing-mortality reference points ($SSB > SSB_{msy}$ and $F < F_{msy}$). These results are not necessarily contradictory to what is presented here, as the LB-SPR estimates per-recruit spawning potential relative to an unfished state, while SS3 estimates spawning biomass relative to a reference point that incorporates many aspects including recruitment compensation. A stock can therefore be near or above SSB_{msy} while still exhibiting relatively low SPR, suggesting that the stock may be near its biomass target but show a reduced per-recruit reproductive output relative to unfished conditions. These results should therefore be considered as a complementary indicator for this stock, and continued monitoring of the size-composition alongside CPUE-based indicators is recommended.

For FAL, the LB-SPR analysis indicated that SPR in the longline fishery was consistently close to the 20% limit reference point across most years, while in the purse seine fishery the estimated SPR was close to zero. The purse seine results, in particular, suggest that measures to reduce the capture and mortality of juvenile FAL would be beneficial to the stock. The effectiveness of any such mandatory releases measure would strongly depend on post-release mortality, which has been estimated to be relatively high for silky sharks captured in purse seines (e.g., Hutchinson et al., 2015). This means that efforts for the implementation of best handling and release practices to increase the post-release survivorship would be needed.

The FISHBLICC results for blue shark and silky shark are largely consistent with those from LB-SPR. Simulation work (Medley, 2025) confirms high consistency between the two frameworks, as both are based on similar dynamics, although LB-SPR uses an age-structured approach whereas FISHBLICC is fully size-structured. This application demonstrated several powerful features of FISHBLICC, namely the flexibility to adopt a range of selectivity functions (asymptotic vs dome-shaped), and the ability to simultaneously fit length data from multiple gears or fisheries. This potentially allows more accurate estimation of fishery-specific selectivity and can reduce bias in SPR estimates.

For OCS and SPL, the available size-composition data were too limited to support a LB-SPR assessment, and the only the per-recruit analyses based on life-history characteristics was conducted. These indicated high sensitivity to fishing mortality for both species. Both species are already recognized as being of particular conservation concern, with OCS already subject to IOTC no-retention measures since 2013 (IOTC Res 25/08). For both species, improved size-composition sampling and biological information remain the principal requirement for any future assessment.

Several assumptions need to be considered when using those data-limited methods. The methods assume that the size composition represents fish removed from the population, but in cases where specimens are discarded (especially if post-release survival is high), the actual fishing mortality will be lower than what has been estimated, and the corresponding status more optimistic. The methods also assume equilibrium conditions and a length composition representative of the exploited population, which is difficult to verify for bycatch species that are mostly sampled opportunistically and that may contain years with limited or atypical sampling.

Another major consideration of those methods is their high sensitivity to the assumed life-history parameters. Specifically, for the IOTC pelagic sharks considered here, growth and maturity parameters are still highly uncertain for many species, and in some there was the need to use parameters from other oceans, adding further uncertainty to the results.

Neither LB-SPR nor FISHBLICC are designed to model length frequencies as a time series. Each annual length frequency is assumed to represent an equilibrium condition, and the models do not account for the dynamics between sampling periods or the cumulative effects of fishing. Nevertheless, annual estimates still provide useful “snapshots” of population status under the equilibrium assumption. While estimates from individual length frequencies may be biased due to interactions among mortality, selectivity, growth, and recruitment variability, trends in the time series are less likely to be affected by these confounding factors, provided they impact the entire series consistently. As such, time series estimates can serve as a useful monitoring tool for detecting trends in population abundance and fishing pressure. An enhanced module has also been developed to allow selectivity parameters to be shared across the time series, which would enable more comparable estimates of fishing mortality and SPR over time (P. Medley, pers. comm).

Despite these limitations, the analysis carried out provides a useful, even if preliminary, indication of the relative vulnerability and status of these shark species in IOTC. For the future, we recommend improving region-specific life-history information, together with better characterization of selectivity through consistent data collection programs, and quantification of discard rates and post-release survival. This would reduce the uncertainty when applying those size-based data-limited assessment methods.

5. Acknowledgments

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