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Length-Based Assessment Methods for the Conservation of a Pelagic Shark, *Carcharhinus falciformis* from the Tropical Pacific Ocean

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Abstract: The silky shark, *Carcharhinus falciformis* is one of the most heavily exploited sharks, being the main by-catch species in both tuna longline and purse-seine fisheries in tropical waters worldwide. Despite this severe exploitation, little is known about the species' life history and population status. Silky sharks, like many other sharks, exhibit slow growth and low fecundity, indicating the urgency of developing assessment studies to aid in the implementation of conservation plans for their stocks. Because information on the catch and effort of this species is scarce, some length-based data-limited methods were applied in the present study to provide estimates of the status of the tropical Pacific silky shark population. As evident from the LBSPR analysis, the current spawning potential ratio (SPR) was found to be below the target reference point of SPR 40% and slightly above the limit reference point of SPR 20%. In addition, the LBB model also confirmed that this stock's status is overfished with relatively low biomass levels. Furthermore, both models showed estimates of size selectivity at 50% and 95% that were lower than the estimated size at sexual maturity. In conclusion, the data-limited models developed in this study indicated that the silky shark stock in the tropical Pacific Ocean may be at risk of further decline. Additionally, the results show that growth and recruitment overfishing may be occurring in the silky shark's population calling for immediate intensification of monitoring programs for these sharks as a pre-requisite to develop efficient management and conservation plans in the Pacific Ocean.

Keywords: data-limited methods; life–history information; by-catch species; size composition

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1. Introduction

Most commercial pelagic fisheries target high-value species such as tuna and swordfish. However, the fishing gear used to capture fish specimens (longlines, purse seines) not only capture targeted species but also non-targeted (by-catch) species such as sharks, small pelagic species (scombrids), and many others. Some of these bycatches are discarded or kept without recording the catch or biological information. Despite their low value in comparison to targeted species, these by-catch species play an important role in subsistence (sustenance and food security) and income-generating means for local populations [1], as well as in balancing the marine ecosystem by regulating the marine trophic web.

According to the most recent FAO report [2], only approximately 12% of the world's fisheries are properly managed or have sophisticated stock assessments for management purposes. Conventional population assessments, (e.g., age structure population models) require large amounts of data such as long-term series of catch-at-age, abundance indices, and fishing effort data that are often not available in data-limited fisheries, especially for many shark species [3]. However, for fisheries with little readily available data (length data), indicators and thresholds (reference points) can be used to assess their status in terms of current biomass, reproductive capacity, and sustainability.

Silky shark (*Carcharhinus falciformis*) inhabits both oceanic and coastal pelagic waters with a circumglobal distribution mainly in tropical regions [4,5]. Their distribution around tropical waters spatially overlaps with that of tropical tunas mostly targeted by purse seine and longline fisheries [6]. Hence, this species is among the most important elasmobranch by-catch species in commercial tuna purse seine and longline fisheries [7–9]. In the quest for cheap sources of animal protein and high prized fins, sharks such as the silky shark are being harvested in high numbers by longline, purse seine, and artisanal fisheries as either targeted species (mainly longline and artisanal fisheries) or incidentally caught (by-catch) species [10,11]. Thus, causing a decline in the population of more than half of shark species [12,13]. Silky shark constitutes one of the three most common shark species in the shark fin trade worldwide, which reflects their high landings [14,15]. Because of all these happenings, important and practical by-catch mitigation measures need to be developed and implemented for this species.

Collecting length data is broadly straightforward and cheap and is one of the most widely used kinds of data accessible to fisheries scientists to assess data-poor fisheries [16]. In view of the simplicity of collecting length data, numerous length-based stock assessment methods for scientifically based fisheries management have therefore been developed in recent decades [17–23]. Although length-based approaches are not as robust as catch-based approaches, they can still generate less biased and reliable estimates [19]. Thus, when fisheries with representative length-composition data are available, length-based techniques can be applied to take initial management actions in a data-limited fishery [19].

Therefore, this study seeks to assess the population status of silky sharks collected in the tropical Pacific based on length composition data utilizing two different methodological approaches. The widely used length-based spawning potential ratio (LBSPR) [24] that assesses the impact of current fishing activities on the reproductive biomass of stocks. In addition, the length-based Bayesian biomass (LBB) estimation approach recently developed by Froese et al. [22] that can be applied to estimate growth and mortality parameters, relative exploitation levels and stock size by using length-frequency data for the fishery analyzed are populations where all appropriate parameters are estimated by the Bayesian Monte Carlo Markov chain (MCMC). The conclusions from the present study will complement existing knowledge about this species and can also be used to provide a basis for viable management recommendations for the Pacific tropical silky sharks.

2. Materials and Methods

2.1. Data Collection

Data used in this study were collected by observers onboard the Chinese tuna longline vessels operating in the Pacific Ocean from 2010 to 2020. These data were spatially limited to the western, central, and eastern tropical Pacific Ocean (20° S–15° N and 147°–100° W: Figure 1). These Chinese tuna longline vessels targeted mainly albacore (*Thunnus alalunga*) and bigeye tuna (*Thunnus obesus*). Well-trained scientific observers were deployed randomly onboard these longline vessels to collect fishery-related data of target and non-targeted species catches, alongside other information about the fishing operation. During their trips, and for each fishing set, the observer records information about the fishing activities witnessed during the trip (set day and hour, set type, set position, and catch information of target (tunas) and by-catch species (in number). Each caught silky shark was measured on board as fork length (FL) to the nearest lower cm, weighed as total weight in kg, maturity stage recorded, and sexed on the basis of the clasper presence. In the Pacific Ocean, in the IATTC region, silky sharks are classified into three categories: (i.e., small (<90 cm total length (TL) or <72 cm fork length (FL)), medium (90–150 cm TL or 72–122 cm FL), large

(>150 cm TL or >122 cm FL)) [25]. This classification was equally applied in this study to classify size categories of captured specimens.

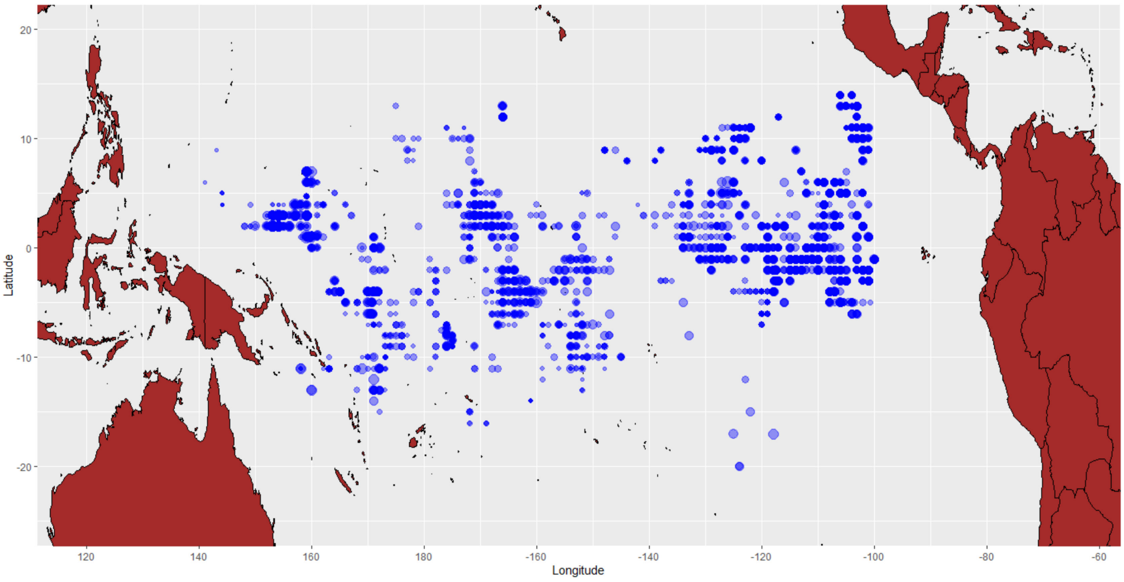

Figure 1. Locations of the study area where silky sharks were recorded in the Pacific Ocean. Blue dots indicate areas where silky shark individuals were recorded.

2.2. Stock Assessment Indicators

2.2.1. Weight-Length Relationship

Fork lengths of captured individuals were grouped into 5 cm class intervals and a similar range was set for the von Bertalanffy growth formula to be estimated in all approaches used. Weight-at-length was described using the power function:

$$WW = aL^b$$

where WW is the whole weight of the individual (kg), L is the recorded fork length of the individual (cm), a is a scaling coefficient and b is an exponent describing the change in L relative to weight.

2.2.2. Estimation of Growth Parameters

The length-frequency data collected for this species was grouped as monthly catches assuming that the obtained sample represents the monthly length distribution of the overall catches. For the estimation of silky sharks' biological characteristics (growth and mortality), an R package, "TropFishR" is based on FAO traditional stock assessment methods [26,27]. The "TropFishR" [27] package used the following von Bertalanffy growth formula to estimate the growth parameters [28] using electronic length frequency analysis (ELEFAN) procedure for the fitting process [29,30]:

$$L_t = L_{inf}\left(1 - e^{-(K(t-t_0))}\right),$$

where L_t is the length of the fish at time t, L_{inf} is the asymptotic length of the species in cm, K is being the rate at which L_t reaches L_{inf} in (year^{-1}), to is the theoretical age of the species at which L_t is equal to zero. A length-length relationship for silky sharks in FishBase was used to convert FL to total length (TL): TL = 1.888 + 1.241 × FL.

2.2.3. Natural Mortality Estimate (M)

Direct estimates of natural mortality (M) for most sharks including silky sharks are not available. Hereafter, using the estimated growth parameters, a set of six different methods and formulae were used to estimate empirical scalar values of natural mortality (M) [31–36]. To simplify the model analyses, the natural mortality based on the median value from the six methods above, was assumed to be constant for subsequent analyses. The analysis was conducted using the TropFishR package version 1.6.3 [37], available at: https://github.com/tokami/TropFishR (access on 17 April 2022).

2.2.4. Estimating Size at Maturity $L_{50\%}$ and $L_{95\%}$

For the length at first sexual maturity ($L_{50\%}$) estimation, maturity stages were grouped into five stages (I to V) for female sharks and two stages (I and II) for male sharks as indicated in Wu et al. [38]. The total combined size frequency data (cm) of mature females (stages III to V) and mature males (stage II) were used for the estimates of $L_{50\%}$ [38]. The proportion of mature individuals by 5 cm FL size class was used to fit the length-based maturity ogives and to estimate $L_{50\%}$. The logistic curve was fitted by non-linear least squares and the parameter values were obtained with the logistic model [39]:

$$\mathrm{Pi} = \frac{1}{1 + e^{-r(Lt - \mathrm{L50\%})}}$$

where Pi is the proportion of mature individuals in the length interval *i*; *r* is the slope of the logistic curve; *Lt* is the total fork length (cm) of the length interval; $L_{50\%}$ is the length at first maturity. A Bayesian method was used to estimate the parameters of the logistic model [38,40]. The sizeMat package version 1.1.2 within the R software was used for this analysis.

The size at 95% maturity ($L_{95\%}$) for silky sharks was estimated based on the equation proposed by [41]:

$$L_{95\%} = 1.1 * L_{50\%}$$

Estimates of L∞, M, and K values by "TropFishR" and the maturity estimates of $L_{50\%}$ and $L_{95\%}$ served as input parameters for the LBSPR and LBB models.

2.3. The Length-Based Spawning Potential Ratio (LBSPR) Model

The use of the LBSPR model requires only size composition data assumed as representative of the exploited population at steady state, and input estimates of key life history parameters. For the purpose of the present study, to analyze spawning potential ratio (SPR), only size data for female silky sharks was used. In the LBSPR approach, SPR in an exploited population is a function of the ratio F/M, selectivity and the two life–history ratios M/K and $L_{50\%}/L_{inf}$ [23]. In addition, it uses catch length composition data to estimate the SPR. Notably, SPR estimates between 0.35 and 0.4 are generally associated with a stock at MSY levels, while SPR estimates below 0.2 suggest the stock is on the verge of collapse. LBSPR is an equilibrium-based technique with some underlying assumptions including (i) asymptotic selectivity, (ii) growth adequately described by the von Bertalanffy equation, (iii) a single growth curve can be applied to describe both sexes which have equal catchability, (iv) length-at-age is normally distributed, (v) rates of natural mortality are constant across adult age classes, (vi) growth rates remain constant across the cohorts within a stock, and (vii) constant recruitment [24].

At its development, the selectivity assumed by LBSPR follows a logistic function, whereby, larger specimens in an age class are reduced in number relative to the smaller specimens in the same age class of that population, usually referred to as the "Lee's Phenomenon" [24]. If this phenomenon is not taken into account, LBSPR is likely to overestimate fishing mortality in cases when selectivity is length dependent. So, to take into account Lee's phenomenon, an extended version developed by Hordyk et al. [42], known as the growth-type-groups (GTG)-LBSPR, which is a length-structured version of the LBSPR method that accounts for length-based selectivity, was used in the present study. This extended version of LBSPR uses the same input parameters as the main approach. The spawning potential ratio (SPR) is defined as the proportion of the unfished reproductive potential left at a selected level of fishing pressure [42]. The GTG-LBSPR model controls differences in fishing mortality rates within the same age class due to the combination of size-dependent selectivity and variability in growth trajectories (Lee's phenomenon). More details of this approach are well developed in Hordyk et al. [24]. In our work, this extended GTG-LBSPR will hereafter be referred to as "LBSPR".

The inputs to the LBSPR are M/K, L_{inf}, $L_{50\%}$ and $L_{95\%}$. The L_{inf}, K and $L_{50\%}$ priors were set equal to the best estimation from the ELEFAN GA bootstrap (TropFishR) and estimated from the size at maturity. The LBSPR model applies maximum likelihood techniques to evaluate the selectivity ogive, which is expected to be a logistic curve described by the selectivity-at-length parameters SL50 and SL95, and the relative fishing mortality (F/M), which are then utilized to estimate the SPR [23]. Estimations of SPR are principally determined by the size of fish in a sample, relative to the maturity and L_{inf}. For example, if a reasonable fraction of fish in a sample attains lengths approaching L_{inf}, evaluations of F/M will be comparatively low leading to a high estimate of SPR [19]. Given that the sample sizes and numbers used in the present study represent the three categories' size classes (juvenile, subadult and adult sharks) defined above, thus assumed to be representative of the population.

Given that sample size for some years was low, we evaluated the influence on the LBSPR output by aggregating the size data set into a single year (2010–2020) and into three-year groups (2013: 2010–2013, 2017: 2014–2017, and 2020: 2018–2020). For these two cases, LBSPR model was used to estimate SPR, gear selectivity (SL50 and SL95; lengths at 50% and 95% selectivity), and the ratio of fishing mortality to natural mortality (F/M). The LBSPR analysis was adjusted using the LBSPR R package version 0.1.7 [43], available at: https://CRAN.R-project.org/package=LBSPR (access on 5 July 2022).

2.4. The Length-Based Bayesian Biomass (LBB) Model

The LBB technique is an easy and fast technique that applies a Bayesian Monte Carlo Markov Chain (MCMC) technique to provide a proxy for relative stock size using only length-frequency data (LFDs) and length at first capture (Lc, if available) [22]. This technique gives estimations of L_{inf}, length at first capture, relative natural mortality (M/K), and fishing mortality relative to natural mortality (F/M). The LBB also calculates an approximation of the currently fished biomass in relation to the unfished biomass (B/B_0) and the current relative stock size (B/B_{MSY}). The annual LFDs used in the present study were aggregated into a single annual dataset to perform an analysis using the LBB under the steady-state assumption.

The L_{inf} prior was set equal to TropFishR's best estimate. In assigning M/K priors, K was set equal to our best estimate of TropFishR, while the length at sexual maturity ($L_{50\%}$) was set according to the estimated value obtained in the present study. All other input parameters were set to the default values mentioned in [22]. Given the estimated B/B_{MSY} values, the stock size of the silky shark was classified based on the value of B/B_{MSY} as in [44]; healthy stock status was assigned if $B/B_{MSY} > 1$; a slightly overexploited state with $0.8 < B/B_{MSY} \leq 1$; overfished where $0.8 \leq B/B_{MSY} \leq 0.5$; heavily overfished state with $0.5 < B/B_{MSY} \leq 0.2$, and for a collapsed state when $B/B_{MSY} < 0.2$. Froese et al. [22] also defined B/B_0 (0.4–0.5) as the reference limit of stock biomass in LBB. The estimated parameters translate into catch size rules: if the relative stock size is $B/B_0 < B_{MSY}/B_0$, the catches would be better reduced, and if the mean length at first capture is $L_c < L_{c\_opt}$, the fishery would be better with larger sizes at the start. With these two basic and simple rules, the application of LBB can be used directly in fisheries with limited amounts of data for preliminary management of fish populations. L_{opt} is the length at which an unexploited cohort has the maximum biomass, L_{c_opt} the optimal length at first capture for specific fishing mortality (F), and L_c the current length at first capture in the fished stock.

The length-frequency data used in this study were analyzed in the R statistical environment version 4.1.3 [45] using the LBB version software 33.

3. Results

A total of 5205 silky shark individuals were collected between 2010 and 2020, with sizes ranging from 47 to 269 cm FL with females ranging between 47 and 269 and males 51–236. The catch sizes were dominated by individuals between 75–180 cm FL with 95% of individuals being smaller than 200 cm FL (Figure 2). The largest female individual identified in this study was 269 cm FL caught in the western Pacific; the largest male (236 cm FL) and the smallest (36 cm FL) shark recorded were both captured in the central Pacific.

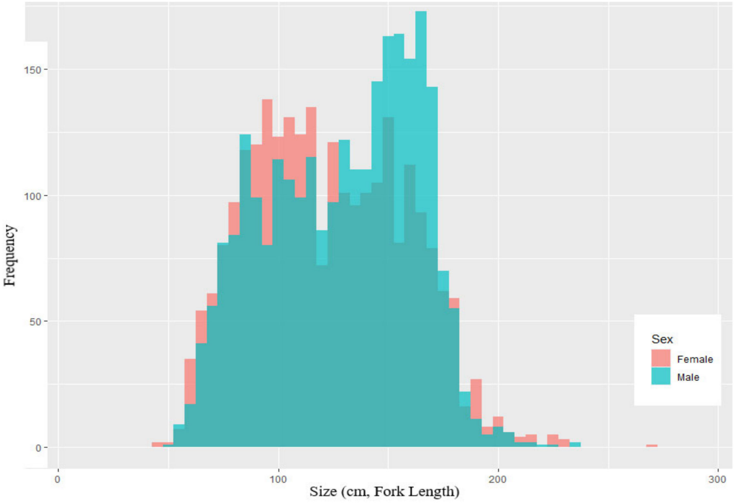

Figure 2. Size frequency distribution of silky shark (5205) from 2010 to 2020 (aggregated). The pink color indicates female sharks (2527), light blue color indicates male specimens (2678), and the medium shade blue is an overlap between female and male silky sharks.

3.1. Weight-Length Relationship

The weight–length relationship was WW = $0.00944FL^{3.094}$ ($R^2 = 0.91$) (Table 1, Supplementary Figure S1). These values were used as input parameters in the LBSPR model.

Table 1. Input parameter values used in this study for the Silky shark (two length-based models tested).

Parameters	Symbol	Parameter Estimates	LBSPR	LBB
Length-Frequency Data	**LFD**		🟩	🟦
von Bertalanffy asymptotic Length	L_{inf} (cm, FL) (cm, TL)	318 (396.5)	🟩	🟦
von Bertalanffy growth parameter	K	0.058	🟩	
Length where 50% of the fish are mature	$L_{50\%}$ (cm, FL)	135	🟩	🟦
Length where 95% of the fish are mature	$L_{95\%}$ (cm, FL)	148.5	🟩	
Length–weight relationship parameter a	a	0.00944	🟩	
Length–weight relationship parameter b	b	3.094	🟩	
Natural mortality (median)	M ($year^{-1}$)	0.173 (0.077–0.257)	🟩	
M/K invariant	M/K	2.983	🟩	🟦
Coefficient of variation of von Bertalanffy asymptotic length (L_{inf})	CV L_{inf}	0.1	🟩	

3.2. Estimates of Growth Parameters, Natural Mortality, and Size at 50% and 95% Sexual Maturity

3.2.1. Growth Parameters

The mean von Bertalanffy predicted growth parameters provided by the ELEFAN procedure in the TropFishR package were 318 cm FL for L_{inf} and 0.058 year^{-1} for the growth coefficient K (Table 1, Supplementary Figure S2). This implies that silky sharks can reach larger sizes and shows a slow growth rate. The ELEFAN procedure within the TropFishR package estimated the mean growth performance index to be 3.766 with a high goodness of fit value (Rn) of 0.262.

3.2.2. Natural Mortality Estimates (M)

As mentioned in the methods section, six different methods were used to estimate M. These methods produced values ranging between 0.077 year^{-1} (Alverson_Carney) and 0.257 year^{-1} (Then et al., 2015, based on growth parameters (L_{inf} and K) (Table 2). The median value of all estimated mortality parameters, with the median being that over the six methods, was 0.173 year^{-1} (Table 1).

Table 2. Natural mortality (*M*) methods and equations used. The parameters L_{inf} and *K* are obtained from the von Bertalanffy growth function, *Tmax* is the maximum observed age, reported *Tmax* for silky shark is 25 years (FishBase, [46]), and T is the temperature (°C). In this study the temperature was assumed as T = 19 °C.

Acronym	Equations	Estimated	References
Pauly_Linf	$M = e^{-0.0152+0.6543*\ln(K)-0.279*\ln(L_{inf}))+0.4634*\ln(T)}$	0.120	[33]
Alverson_Carney	$M = \frac{3K}{e^{(0.38*Tmax*K)-1}}$	0.273	[32]
Then_1	$M = 4.899 * Tmax^{-0.916}$	0.257	[36]
Then_2	$M = 4.118 * K^{0.73} * L_{inf}{}^{-0.33}$	0.077	[36]
Hewitt Hoenig	$M = e^{1.44-0.98*\ln(Tmax)}$	0.180	[35]
Hoenig	$M = e^{1.46-0.101*\ln(Tmax)}$	0.167	[34]

3.2.3. Estimating Size at-$L_{50\%}$-and-$L_{95\%}$ Maturity

The estimated size where 50% proportion of silky sharks were mature was 135 cm, FL and the calculated size at 95% maturity was 148.5 cm, FL (Table 1, Supplementary Figure S3).

3.3. Estimation of Biological Reference Points (BRP) and Stock Status

3.3.1. Estimates Provided by the LBSPR Model

The size at 50% and 95% maturity were estimated at 135 and 148.5 cm FL, respectively. The life–history ratio (M/K) was calculated to be 2.983 based on the median natural mortality (0.173 y^{-1}) obtained from six indirect methods. Other parameters used to perform the LBSPR assessment are presented in Table 1. The estimated growth curve by LBSPR fits well with the distribution of length data (Supplementary Figure S3). For the two dataset types defined in the present study, the LBSPR model provided estimates of the last year of SPRs of 27% and 28% (Figure 3) and relative fishing mortality (F/M) ratios below unity (0.71) for the aggregated years and the last three years datasets. The SPRs obtained for both datasets are well below the target reference point of SPR 40% and but slightly above the limit reference point of SPR 20% (Table 3). However, a strong difference was found between these results and the values corresponding to 2010–2013 (sustainable fishing mortality and high SPR) and 2014–2017 (overfishing and very low SPR) (Table 3). This might be attributed to the difference in sample sizes with the former having a much lower sample size than the latter.

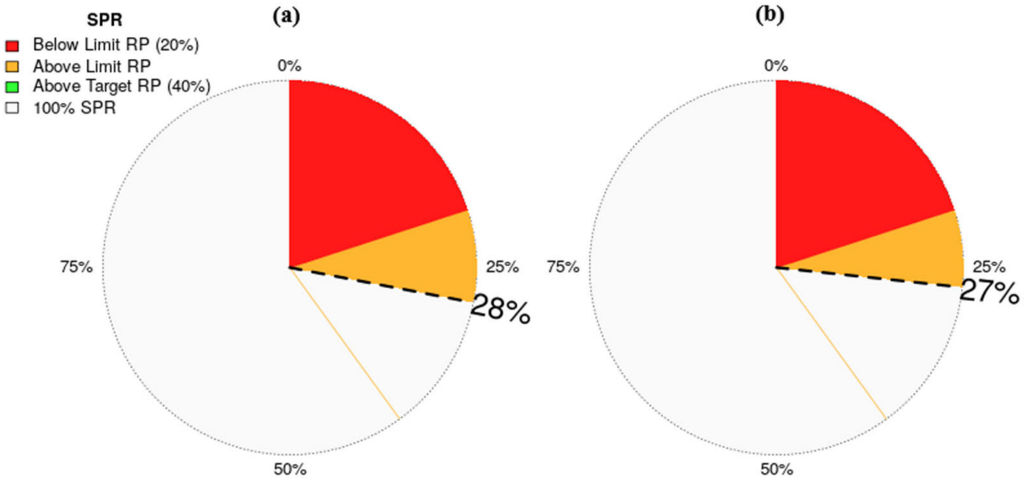

Figure 3. Current spawning potential ratio (SPR) proportions by category of SPR-based reference points for the silky shark in the Pacific Ocean. (**a**) Represents the aggregated year, (**b**) SPR corresponding to the last three years period (2018–2020).

Table 3. LBSPR annual raw estimates of selectivity (SL50, SL95), fishing pressure (F/M), and spawning potential ratio (SPR) with 95% confidence interval.

Length Composition Aggregated into One Year (2010–2020)				
Aggregated Year	**SL50 (CI)**	**SL95 (CI)**	**F/M (CI)**	**SPR (CI)**
2010–2020	88.72 (84.11–93.33)	122.23 (114.29–130.17)	0.7 (0.57–0.83)	0.28 (0.23–0.33)
Length Composition Aggregated into 3-Year Dataset				
Aggregated Years	**SL50 (CI)**	**SL95 (CI)**	**F/M (CI)**	**SPR (CI)**
2010–2013	63.72 (59.67–67.77)	76.76 (68.01–85.51)	0.13 (0.03–0.23)	0.72 (0.55–0.9)
2014–2017	111.93 (99.65–124.21)	160.86 (142.76–178.96)	1.46 (0.88–2.04)	0.16 (0.09–0.24)
2018–2020	84.83 (81.53–88.13)	108.49 (102.36–114.62)	0.71 (0.58–0.84)	0.27 (0.22–0.32)

Furthermore, most SPR values were below 60%, suggesting an appropriate target reference value for low-productivity species such as sharks [47,48]. The low SPR values observed in this study might be caused by the selectivity type assumed in this study, expressing a possibility of the lack of many larger specimens in the catch used. The specific estimated parameters of SL50, SL95, F/M ratio, and SPR for all dataset types are presented in Table 3 and Figure 4 (Supplementary Figure S4 indicates the maturity and selectivity curves). The estimated selectivity sizes at 50% are below the estimated size at 50% maturity ($L_{50\%}$ = 135 cm FL) characterizing the dominance of younger sharks in the catch (Figure 4). Additionally, smaller lengths at which 95% of silky sharks are likely to be captured were observed. This might also be indicative of the absence of mature, old, and larger sharks in the stock, which is a sign of recruitment overfishing.

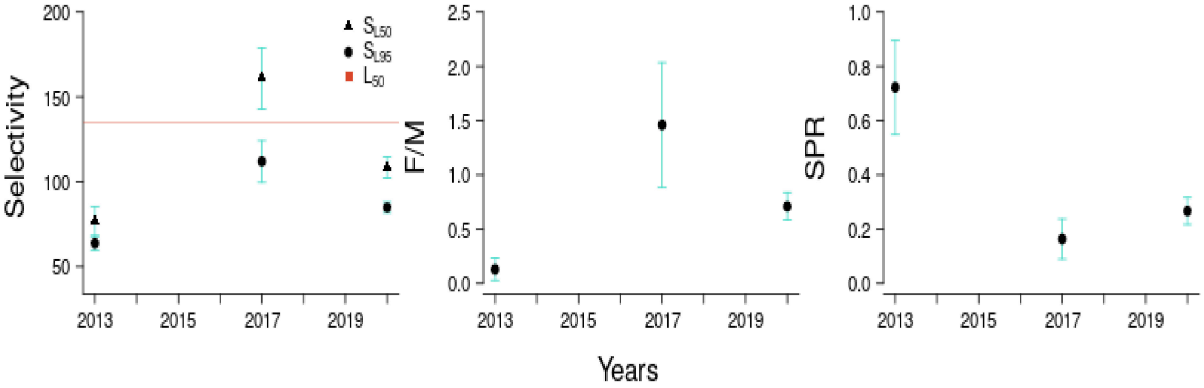

Figure 4. Estimates of selectivity parameters and SPR-based BRPs of the silky shark in the Pacific Ocean. Plot showing estimates when size data are aggregated into a 3-year dataset (2010–2013, 2014–2017, 2018–2020). Red straight line indicates size at 50% maturity ($L_{50\%}$). Green lines indicate confidence intervals.

3.3.2. Estimates Provided by the LBB Model

According to the outputs of LBB, the stock status of the silky shark is likely to be overfished (B/B_0 = 0.2 and B/B_{MSY} = 0.54. The fishing mortality ratio F/M = 2.1 appeared to be twice as high as the fishing mortality corresponding to M as a proxy of MSY, indicating an overfishing status of the stocks.

To ensure healthy spawning biomass, fisheries selectivity should exclude immature specimens from capture to allow them to mature and reproduce at least once in their lifetime. However, since the length at first capture given by LBB (*Lc* = 113 cm FL) is lower than the length at first maturity ($L_{50\%}$ = 135 cm FL), the silky shark population may be suffering of recruitment overfishing. The optimum length at first capture (*Lc_opt* = 147 cm FL) is higher than *Lc* indicative of growth overfishing and a suggestion to target more larger sizes in the future. The estimated relative stock size B/B_0 was smaller than Bmsy/B0, an indication that management might start thinking of reducing catches of silky sharks. (Table 4).

Table 4. Results of LBB analysis with the stock status of silky sharks in the Pacific Ocean. Proxies of the stock status presented by the LBB (L_{inf}, *Lc/Lc_opt*, L_c, F/M, and B/B_0, B/B_{MSY}, B_{MSY}/B_0 and their respective 95% confidence intervals (numbers in brackets)).

Species Scientific Name	**L_{inf} (CI)**	**Lc/Lc_opt**	**F/M (CI)**	**Lc (CI)**	**B/B_{MSY} (CI)**	**B/B_0 (CI)**	**B_{MSY}/B_0 (CI)**	**Stock Status**
Carcharhinus falciformis	316 (309–324)	0.77	2.1 (1.3–3.2)	113 (107–130)	0.54 (0.42–0.61)	0.2 (0.14–0.36)	0.44 (0.24–0.6)	Overfished

Note: *Lc/Lc_opt* = length at first capture of fished stock over optimum length at first capture; B/B_0 = current relative biomass over unfished biomass; B/B_{MSY} = current biomass relative to the biomass capable of producing maximum sustainable yields; F/M = relative fishing mortality over natural mortality. B_{MSY}/B_0 = relative biomass that produces the maximum sustainable yield.

4. Discussion

This study is the first attempt to apply length-based data-limited methods to the silky shark stock in the Pacific Ocean. In particular, two length-based data-limited methods (LBSPR and LBB) were implemented using size data caught by longlines targeting tuna considered representative of the silky sharks' population in the area. Both models assume a logistic selection curve. Although some authors consider that longlines have a bell-shaped curve, like gillnets [26], we followed the suggestion of Soussa et al. [49] and Clarke et al. [50], who considered the logistic function adequate to describe the selectivity pattern of longlines. Furthermore, a suite of indirect natural mortality methods suitable for bycaught species was applied, and their estimated median was used for subsequent analyses. Because it can be difficult to understand stock status in relation to a single biological reference point [51], this study combined two methodological approaches for the best estimates of this fishery that require minimal data input (length data only). However, in the present study, the SPR analysis showed that the current SPR% was below the target value (SPR 40%) but above the limit value (SPR 20%) and the current biomass content (B/B_0) was also low, which may be indicative of an overfished state of silky sharks.

4.1. Growth, Mortality, and Sexual Maturity

Life history parameters are the basic inputs when analyzing the condition of fish stock to make effective management recommendations. TropFishR followed traditional stock assessment methods from length data with a few additional steps to generate more robust and accurate growth estimates. The results of this study did not differ that much from previous estimates of growth parameters, even though this study was conducted using a wider search range input for the bootstrap ELEFAN analysis to cover these estimates [46]. The estimated L_{inf} (318 cm FL = 396.52 cm, TL using the length-length relationship for silky sharks in FishBase) and growth coefficient (K = 0.058/year) values as estimated for silky sharks in the present study were within the ranges given in FishBase (L_{inf}: 198 to 468 cm, TL) and (K: 0.08 to 0. 19). This very wide range in L_{inf} suggests that the samples used in the literature are not adequate to estimate an unbiased VBGF, thus the reason for using our estimated parameters. The sizes reported in the present study were dominated by subadult animals may be because of the selectivity nature of the gear used in the present study, however, had a representation of all three categories of sizes, from juvenile to subadult and adult specimens. Elsewhere, reports in the Atlantic, Indian, and Pacific Oceans also reported a dominance of juvenile and pre-adult silky sharks in catches although they used other fishing gears notably purse seines [6,11,52,53]. The estimated size at maturity $L_{50\%}$ = 135 cm, FL given in the present study was the lowest compared to previous reports of the Pacific Ocean silky shark [54]. This decrease in size at sexual maturity observed in the present work could indicate a decrease in catch sizes, likely due to excessive fishing pressure exerted on silky shark populations. However, to avoid a possible collapse of this stock and to ensure the sustainability of the stock, it would be prudent to capture specimens that are larger than the estimated size at sexual maturity, which was not the case as presented by the present study. Although it is difficult to draw a conclusion based only on this observation, it seems likely that overfishing is partly responsible for the capture of younger silky sharks, given the dominance in the reported catches.

Directly estimating, (e.g., by tagging) the natural mortality (M) of most fish species is costly, difficult, or sometimes impractical, as estimating this parameter for many species, including silky sharks, still depends on empirical approaches. Estimates of natural mortality are critical to understanding the status and dynamics, therefore caution must be exercised when estimating this parameter [36,55]. To estimate the natural mortality rate (M), a multi-method approach with a stepwise process using six different methods was used. Such a parallel implementation of multiple methods for M is not typically used in many studies, and the M value is usually calculated using only one of a handful of M equations. Using many empirical approaches to estimate M can help capture much of the uncertainty in natural mortality within a population model, as this will provide a wide range of possible M values. The median of the estimated values of M in this study; the final value used here fell within the reported M values for silky sharks [46]. To address this, the best-estimated growth parameter values obtained via TropFishR were used in these methods. The use of different M-estimators is often recommended to reduce bias, error, underestimation, and uncertainty of the applied methods [40].

4.2. Diagnosis of the Stock-Based on LBSPR and LBB

4.2.1. LBSPR

The Spawning Potential Ratio (SPR) is an established biological indicator and a powerful tool for assessing the impact of current fishing pressure on the reproductive potential of stocks [23,24]. Determining this SPR ratio is critical to developing an effective fish stock management strategy. This study used the extended GTG-LBSPR method to assess the spawning biomass of the silky shark population. For the estimation of SPR, LBSPR methods showed their robustness, especially in species with M/K > 0.53 and length data composition with uni- or bimodal distribution [2,23]. Because the LBSPR method is very sensitive to input parameters (Linf, K, M, $L_{50\%}$, and $L_{95\%}$) and previously estimated values are highly variable, this study used the estimates generated by TropFishR bootstrap approach and sexual maturity, as input parameters for the LBSPR analysis. In the present work, the size data collected from 2010 to 2020 were divided into two groups to observe whether changes in the size composition data can have an impact on the current SPR of the silky shark stock. As indicated by the LBSPR analysis for the two cases, the Pacific silky shark population may be moderately exploited with a low reproductive potential (SPR = 27–28%) although with sustainable relative fishing mortality (F/M = 0.71 for the aggregated size data or F/M = 0.7 for the recent three-years). When there is a high frequency of juvenile and subadult sharks in the catch composition and a few larger sharks as observed in the present study, higher chances of low SPR values can be generated. Due to the low size at which silky sharks are likely to be captured (SL50% and SL95%), the availability of targeted size classes to maintain the 40% SPR threshold is scarce, which can consequently lead to recruitment overfishing.

4.2.2. Stock Condition Analysis Based on LBB

Although numerous matrices have been developed to analyze data-poor fish stocks' by means of length frequency distribution data, fishing mortality and biomass indicators have been extensively applied to make operational management strategies to control fishing pressure and guarantee stock yield sustainability [56]. An LBB model for the tropical Pacific silky shark was developed using the same input parameters as in the LBSPR analysis. The results suggest that the Pacific silky shark population may be overfished and overexploited, making it more vulnerable. The estimated current exploited biomass relative to unexploited biomass (B/B_0) and current relative stock size (B/B_{MSY}) were all below the target biomass levels, confirming the results of the LBSPR analysis. The fishing mortality relative to natural mortality (F/M) was two times higher than the proxy (F/M = 1) for the relative fishing mortality that can produce the maximum sustainable yield (MSY). However, the result from LBB shows MSY will not be achieved at the current state given the overfishing and overfished state of the stock. The length at first capture (Lc) should be close to or greater than the length at first maturity $L_{50\%}$ to avoid recruitment overfishing, but results indicate size at first capture is below $L_{50\%}$, as estimated by LBB.

The LBSPR and LBB methods require length composition data of all size classes representing the fished population. The presence of silky shark specimens covering all three size categories defined by Aires-da-Silva et al. [25], i.e., small (<90 cm total length (TL) or <72 cm fork length (FL)), medium (90–150 cm TL or 72–122 cm FL), large (>150 cm TL or >122 cm FL) [25] makes available data feasible for stock assessment purposes. Moving on, we found that the LBB model provided a diagnosis of silky shark population status (overfished and overfishing levels) under steady state and asymptotic selectivity assumptions. LBSPR corroborated that this stock is being overfished as observed in LBB but with a relative fishing pressure below unity. This difference in relative fishing mortality between the two models may be attributed to the data set types employed for analysis in both models. LBSPR only used female specimens given that SPR mainly focuses on reproduction, whereas LBB used data of combined sex to run analysis.

It should be recalled that failing to meet the above assumptions may have an effect on SPR (underestimate) and F/M (overestimate) values [24], because larger specimens may not be fully represented in the analysis. As applied in the present study, the developed GTG-LBSPR that counters this phenomenon called the "Lee phenomenon" was preferred over the original LBSPR but selectivity was still assumed to be asymptotic. However, Marta et al. [57] applied this method to Iberian stocks with similar assumed selectivity and obtained reliable results. However, it would be important to further verify the shape of the selectivity curve for silky sharks, for example by using fishery-independent data or by evaluating changes over time in the length-composition of the catch.

Fisheries management organizations such as IATTC, WCPFC, ICCAT, and IOTC are mainly in charge of developing stock assessments for the conservation of tunas and large pelagics in their areas of competence. These organizations often use assessment models, (e.g., SS3, Stock Synthesis version 3) that require a considerable amount of data routinely collected, which is most challenging for many untargeted or/and by-catch species, such as sharks, generally having insufficient, unreliable, or/and misreported catch and abundance indices data. Given the development of a suite of data-limited approaches used in many other fisheries that showed positive results, and also given the availabilities of easy-to-collect data such as length. Clarke et al. [58] in the Pacific Ocean used the SS3 model assessment framework and life history parameters to assess silky sharks. Their results showed that a large number of abundance indices (CPUE) were previously closely correlated with key oceanographic conditions and therefore may not represent reliable abundance indices for this stock. Although results from this study were not recommended for management decisions due to conflicting abundance indices, their assessment results also indicated that silky shark biomass has declined significantly, and fishing mortality has increased significantly over the past two decades. These results are confirmed by the results obtained in the present study when we used both the LBSPR and LBB methods with a large sample of length composition data. In the Indian Ocean, Ortiz de Urbina et al. [59] presented a preliminary assessment of the silky shark using a Monte Carlo data-limited model, to catch maximum sustainable yield (CMSY). Their result showed that the silky shark stock in the Indian Ocean is subject to overfishing, but not yet overfished. Given the lack of assessment for this stock, they indicated the need to use their work as a starting point for future assessments of the silky shark in the Indian Ocean.

5. Conclusions

Results from both methods used in the present work indicate that this fishery is in an overfished state with a low reproductive potential of the stocks. Contrastingly, both models presented different levels of relative fishing pressure, which may be a result of the use of different datasets in LBSPR (only female specimens) and LBB (all specimens). Furthermore, given the preliminary nature of this work and the uncertainty surrounding the estimated parameters, management advice may be derived from this study with caution. For further studies to assess exploited shark species such as the silky shark, data collection should be improved, and conducting more sophisticated assessments should consider oceanographic indices and study their impact while increasing coverage by longline observers in commercial fisheries to avoid problems related to unrepresentative samples.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes7040184/s1, Figure S1: Weight-length plot from specimens having weight and length measurements; Figure S2: The length-frequency distribution of the silky shark for aggregated catch years as presented by TropFishR package; Figure S3: Size-frequency distribution of observed fished population, and the solid black line show the predicted fished size composition from the fitted LBSPR model; Figure S4: Top image: estimated length at 50% sexual maturity (L50%) and Below image: maturity and selectivity curve from the fitted LBSPR model where thick black curve indicated L50% a and the other colours length at first capture for each analyzed year group.

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