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BAYESIAN LENGTH ANALYSIS AND EXPLOITATION RATES FROM THE MAIN TARGET SHARK SPECIES CAUGHT IN THE NORTHWESTERN MEXICAN PACIFIC: A PREAMBLE TO FISHERY INDICATORS

Análise de comprimento bayesiano e taxas de exploração das principais espécies de tubarão alvo capturadas no noroeste do Pacífico mexicano: um preâmbulo para indicadores de pesca

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ABSTRACT

Sharks in Mexico have economic, fishing, and social importance; however, there are no complete assessments of their populations, mainly due to scarce and inadequate catch and effort data. Nevertheless, through size frequency analysis, it is possible to obtain preliminary fishing indicators to know the status of an exploited population. This study analyzes fishing-dependent data (sizes and sexes) of nine species of pelagic sharks from data collected onboard medium-size shark vessels in the Mexican Pacific from 2006 to 2018. Our results suggest that the average lengths in the catch have remained constant throughout the study period. Similarly, exploitation rates remained below the benchmarks proposed by the literature. However, the results presented in this study should be taken cautiously and only as a preliminary analysis until more complete studies are carried out.

Keywords: bayesian approach, Mexican Pacific, pelagic sharks, total mortality.

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RESUMO

Os tubarões no México têm importância econômica, pesqueira e social. No entanto, não há avaliações completas de suas populações, principalmente devido aos escassos e inadequados dados de captura e esforço. Contudo, através da análise de frequência de tamanho, é possível obter indicadores pesqueiros preliminares para conhecer a situação de uma população explorada. Este estudo analisa dados dependentes da pesca (tamanhos e sexos) de nove espécies de tubarões pelágicos a partir de dados coletados a bordo de embarcações de tamanho médio voltadas para pesca de tubarão no Pacífico mexicano de 2006 a 2018. Nossos resultados sugerem que os comprimentos médios nas capturas permaneceram constantes ao longo do período de estudo. Da mesma forma, as taxas de exploração permaneceram abaixo dos valores de referência propostos pela literatura. No entanto, os resultados apresentados neste trabalho devem ser tomados com cautela e apenas como uma análise preliminar até que estudos mais completos sejam realizados.

Palavras-chave*: abordagem bayesiana, Pacífico mexicano, tubarões pelágicos, mortalidade total.*

INTRODUCTION

Mexico is the 15th largest fish producer worldwide, with an annual production of 1.47 million tons (FAO, 2020). Sharks are one of Mexico's main marine fishes with high socio-economic importance (Castillo-Géniz *et al*., 1998), with 111 recognized species (Ehemann *et al*., 2018). Mexico is historically among the top shark producers worldwide, with an average annual catch of 30,000 t (Bonfil, 1994). However, considered a bycatch, sharks were not a priority for the catch and effort data programs (Compagno, 1990). Shark fisheries have grown driven by the country's demographic growth, which required new animal protein sources during the 1950s and 1960s (Sosa-Nishizaki *et al*., 2020). In addition to fins, mainly meat, liver oil, skin, cartilage, jaws, and teeth are marketed (Tovar-Ávila *et al*., 2020). All Mexican shark meat production is consumed domestically, and shark fins are exported to Asian markets following CITES regulations that have been implemented worldwide in recent years (Del Moral-Flores *et al.,* 2016).

Due to indications of overexploitation in coastal shark fisheries in some regions of Mexico in the mid-1990s, the National Fisheries and Aquaculture Commission (CONAPESCA) and the Mexican fisheries scientific authority, the National Institute of Fisheries and Aquaculture (INAPESCA), prepared and published the Mexican Norm: NOM 029-PESC 2006 (NOM 029) "Responsible Fishing of Sharks and Rays: Specifications for their Use" (SAGARPA, 2007). This portfolio of regulations aims to lay the foundations for the sustainable fishing of sharks and rays in Mexico. The actions include implementing a scientific observer program (SOP) aboard shark vessels in the northern Mexican Pacific. This program collected biometric (size and sex), biological (stage of maturity), and effort data. Tovar-Ávila *et al*. (2011) provided an initial comprehensive outline of catch and catch rate data for pelagic sharks caught by the Mexican shark longline fishery in the North Pacific from data collected during the first years of SOP operations.

In Mexico, most fisheries are considered data-limited because there is insufficient data to conduct a comprehensive quantitative stock assessment to estimate the biomass time-series and fishing mortality relative to their reference points (Dowling *et al*., 2019). Nevertheless, several authors have developed models to evaluate stock status indicators based on the total catch (Froese *et al.,* 2018; Martell & Froese, 2013) or length data (Hordyk *et al.,* 2015b; Rudd & Thorson, 2017). Therefore, data-limited assessment methods are increasingly used for management purposes to report on the regional level of fisheries across many stocks and to assess the status of individual data-limited stocks as inputs to management decisions (Dowling *et al*., 2019). In developing countries, length- frequency data from commercial catches are often the primary data collection because they are relatively low-cost and easy to collect (Hordyk *et al*., 2015a; Mildenberger *et al*., 2017; Pilling *et al*., 2008). The size composition of exploited populations has long been used in fisheries management to estimate stock status (Beverton & Holt, 1956; Gulland & Rosenberg, 1992), the spawning potential ratio (SPR) (Hordyk *et al*., 2015b), and more recently to determine whether size and age structure is comparable to that of a healthy stock (Froese; Demirel & Sampang, 2015).

Surveying sharks over large ocean regions is expensive and impractical (Baum; Kehler & Myers, 2005). Therefore, in many cases, fisheries-dependent data are often the only available source of information to estimate trends in the relative abundance and spatial distribution of oceanic sharks. Although more problematic than survey data (Bishop, 2006), fisheries-dependent data, in some cases, can be used to estimate standardized abundance index methods (Harley; Ransom & Dunn, 2001; Maunder & Punt, 2004). For example, in the North Pacific, the International Scientific Committee for Tuna and Tuna-like species (ISC) has conducted stock assessments for the blue shark (*Prionace glauca*) and shortfin mako shark (*Isurus oxyrinchus*) incorporating abundance index estimated from standardized catch rates from various national longline fishing fleets on integrated stock assessment models (ISC, 2017, 2018). In addition, González-Ania *et al.* (2014) and Fernández-Méndez *et al.* (2016) have estimated the abundance index for shortfin mako and blue shark caught in northeastern Mexican Pacific waters based on data collected from a scientific observer's program.

Despite the limited data in Mexico, the North Pacific shark fishery has endured more than fifty years, with its most intense exploitation period between the 1960s and 1980s (Castillo-Géniz & Tovar-Ávila, 2021). For the most part, the continued existence of this fishery is a result of the conservation measures implemented in Mexican waters in 2006, which indicates that they have been adequate. Nevertheless, it is difficult to assess the possible benefits of these measures quantitatively due to the lack of complete records of total catches, including discards of the main commercial species and systematic monitoring of sizes, sexes, and ages of sharks caught. Furthermore, despite sharks' economic, social, and fishing importance, catch statistics are incomplete, so mortality and exploitation rates are scarce (Worm *et al.,* 2013). Nevertheless, there are estimations of fishing mortality and exploitation rates for some shark species that inhabit Mexican waters (Bada-Sánchez *et al.,* 2019; Chang & Liu, 2009; Hayes; Jiao & Cortés, 2009; ICCAT, 2008; Kleiber *et al.,* 2009; Lessa *et al.,* 2012; Ricard *et al.,* 2012; Smith *et al.,* 1998, 2009; SEDAR, 2011).

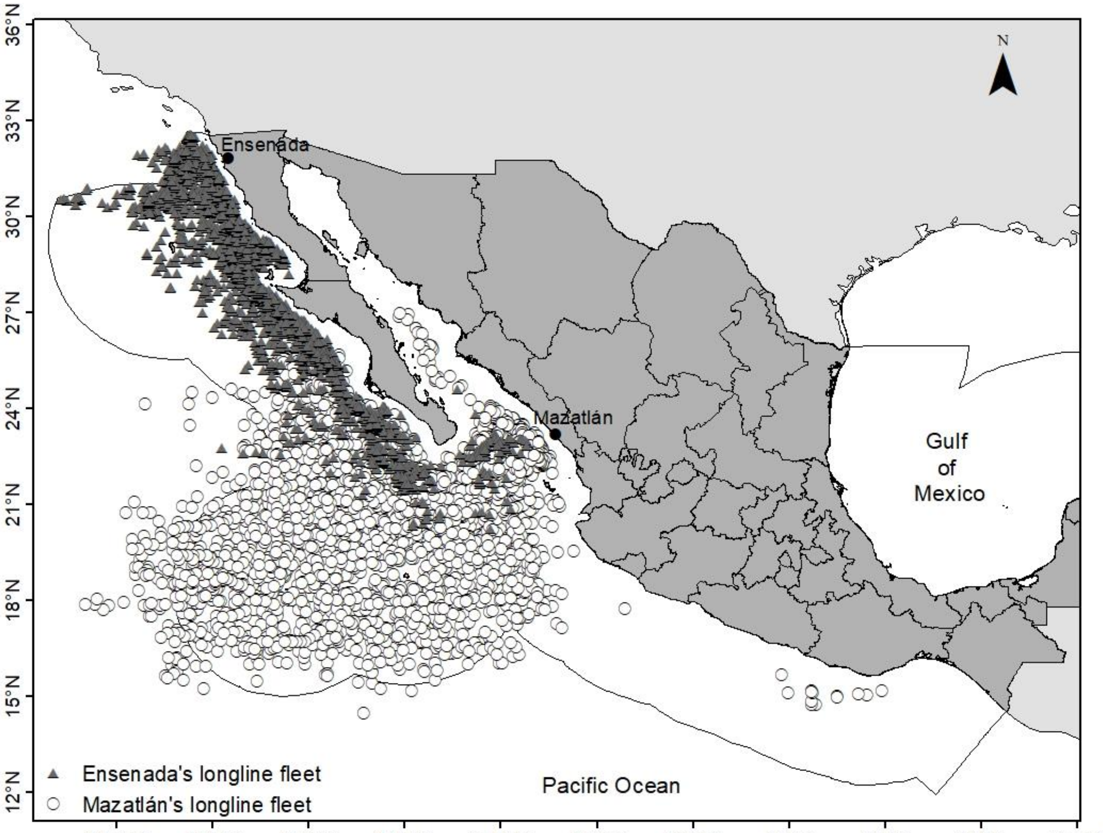
This study describes and analyzes the length composition of the nine most abundant species in landings caught by the longline fishery in the Mexican Pacific using a Bayesian approach. In addition, the mortality and exploitations rates as preliminary stock status indicators are estimated. Finally, results are discussed in light of the application of this type of information and its implications for managing longline fisheries in Mexican Pacific waters.

MATERIAL AND METHODS

Data collection

The Mexican shark observer program of FIDEMAR (Research Trust for the Development of the National Tuna Harvesting Program and Protection of Dolphins and Others around Protected Aquatic Species) collected size and sex data between 2006 and 2018 from the blue shark, *Prionace glauca*; shortfin mako, *Isurus oxyrinchus*; silky shark, *Carcharhinus falciformis*; oceanic whitetip shark, *C. longimanus*; bigeye thresher, *Alopias superciliosus*; common thresher, *A. vulpinus;* scalloped hammerhead*, Sphyrna lewini*; smooth hammerhead, *S. zygaena*, and the great hammerhead shark, *S. mokarran*. These species are caught using the *"J"* hook and *"Mustad Tuna Circle"* hook (0/16). The study area, from 15° to 35° N and from 96° to 122° W, was defined by the distribution of fishing trips (Figure 1). Each specimen was identified, sexed, and measured in precaudal length (PCL) onboard to the nearest centimeter straight along the body axis (Gallegos-Camacho & Tovar-Ávila, 2011).

Figure 1 - Study region (fishing area) including location of surface longline sets where observers obtained shark size and sex data separated by fleet (Ensenada and Mazatlan) in northwestern Mexico during 2006-2018.



Length and sex analysis

Size frequency histograms were constructed to describe the size structure of the organisms during the study period. The Bayesian approach (Doll & Jacquemin, 2018) was used only to compare the observed sex ratio to the expected value and for the linear models comparing mean lengths between sexes and years.

First, the observed sex ratio was compared to the expected sex ratio (1 Female: 1 Male) for the overall sample of each species using the chi-square statistic: $\chi^2 = \sum (O_i - E_i)^2/E_i$., where O_i is the observed frequency by sex (i indicates male or female), and E_i is the expected frequency under a null hypothesis of 1:1.

The chi-square statistic is modeled using a χ^2 distribution with a centrality parameter k (degrees of freedom). Next, we evaluate the evidence that the null hypothesis (1:1) is true, modeled by a chi-square distribution with one degree of freedom, which is the distribution the chi-squared statistics would take for a chi-square contingency test with two groups (male vs. female) if the sex ratio were 1:1. The prior for k was defined as a uniform distribution (UD): k UD (0.01, 100) (Johnson, 2004). Finally, the probability that the sex ratio differed from 1:1 was calculated as the posterior probability that k was greater than 1 (the expected value under the null hypothesis) estimated using Monte-Carlo Markov Chain (MCMC) throughout the R-packages "R2jags" (Su & Yajima, 2012). To determine if the mean of the sharks' precaudal length (PCL) varied between two factors: sexes (α) and years (β), we used a two-way ANOVA. We used a Bayesian hypothesis test through the Bayes factor (Kass & Raftery, 1995) as a model selection method.

$$\left[BF_{10} = \frac{P(Data|H_1)}{P(Data|H_0)}\right] \tag{1}$$

First, we set the null hypothesis (H_0) as effect size (δ) = 0. For the alternative hypothesis (H_1), we place a Cauchy prior distribution for δ with a location parameter of 0 and a scale parameter of 0.707 for each factor. For sexes, δ is the standardized difference of the means (μ_j – μ_j/σ; where μ_j is the mean of each sex, and σ the standard deviation). For years, β is the standardized mean of all years (μ/σ; where μ is the general mean and σ the standard deviation). Finally, to test whether there is any factor effect, we used the corresponding Bayes factor comparisons BF_α and BF_β appropriate for assessing differences between sexes and years, respectively. We assume normal probability distribution of the data. The setup described here is drawn on and extended in Bayesian methods for model selection (O'Hara & Sillanpää, 2009; Rouder *et al.*, 2012).

We used one MCMC with 100,000 iterations to estimate the posterior probabilities. The first 5,000 iterations were discarded to avoid autocorrelation, and every tenth iteration was saved (Smart & Grammer, 2021). We used the R-package "Bayes Factor" (Morey *et al.*, 2018) and followed Goss-Sampson guidelines for Bayes factor interpretation (Table I). We used trace plots (Gelman & Rubin, 1992) and Raftery and Lewis's diagnosis (1992) to monitor the convergence of MCMC output.

All statistical analyses were conducted using Microsoft Excel 2016 and statistical software R, vers. 4.0.3 (R Core Team, 2020).

Table I – Descriptive classifications to interpret Bayes factor. BF_{10} = Bayes factor.

BF_{10}	**Evidence**	**In favor of**
>100	Decisive	Alternative hypothesis
30 to 100	Very strong	Alternative hypothesis
10 to 30	Strong	Alternative hypothesis
3 to 10	Moderate	Alternative hypothesis
1 to 3	Anecdotal	Alternative hypothesis
1	No evidence	Neither
1 to 0.33	Anecdotal	Null hypothesis
0.33 to .1	Moderate	Null hypothesis
0.1 to 0.033	Strong	Null hypothesis
0.033 to 0.01	Very strong	Null hypothesis
< 0.01	Decisive	Null hypothesis

Mortality Rates

Natural mortality (M) and total mortality (Z) were estimated to calculate fishing mortality ($F = Z\text{-}M$). First, we calculated M through six indirect methods (Hamel, 2015; Jensen, 1996, 1997; Then *et al*., 2015) based on each species' average life history parameters (Table II). Then, to estimate the confidence intervals ($CI_{95\%}$), we resampled M using the bootstrap method (Ritz & Streibig, 2008) with 1000 resamples.

To calculate the total mortality rate (Z), first, we convert length into ages using the life history parameters (Table II) and the inverse von Bertalanffy equation:

$$t_L = t_0 - \frac{1}{K}\ln\left(1 - \frac{PCL}{L_\infty}\right) \tag{2}$$

Where t_L is the age at length, t_0 is the theoretical age when the organism's size is 0 cm, K is the somatic growth rate, PCL is the precaudal length, and L_∞ is the asymptotic length.

Table II – Life history parameters. L_∞: theoretical maximum length (PCL*, cm); K: growth coefficient (year^{-1}); t_0: theoretical age at a length of zero (years), and longevity (years).

Species	L_∞	**K**	**Longevity**	t_0	**Zone**	**Reference**
Prionace glauca	329.6	0.11	20	-0.76	North Atlantic Ocean	Nakano and Stevens (2008); Skomal and Natanson (2003)
Isurus oxyrinchus	339	0.05	18	-4.7	Mexican Pacific	Ribot-Carballal *et al.* (2005);
	308	0.09	20		North Pacific Ocean	Semba *et al.* (2009)
	255	0.08	25	-3.68	Pacific Ocean	Cerna and Licandeo (2009);
	306	0.09	30		Mexican Pacific	Soriano-Velásquez *et al.* (2006)
Carcharhinus falciformis	210.9	0.15	12	-2.32	Mexican Pacific	Cruz-Jiménez *et al.* (2014);
	182	0.14	16	-2.98	Mexican Pacific	Sánchez de Ita *et al.* (2011)
	264	0.04	19	-6.53	Mexican Pacific	Cervantes-Gutiérrez (2013)
Carcharhinus longimanus	230	0.05	18		Western North Pacific Ocean	D'Alberto Brooke *et al.* (2016)

(continuation Table II)

Species	L_∞	K	Longevity	t_0	Zone	Reference
Carcharhinus longimanus (cont.)	225	0.08	9	-3.65	Western North Pacific Ocean	Shoou-Jeng *et al.* (2016)
	237	0.08		-3.34	Southwestern equatorial Atlantic	Lessa *et al.* (1999)
Alopias superciliosus	249.5	0.06	22		Atlantic Ocean	Fernández-Carballo *et al.* (2011)
	221	0.09	20	-4.2	Northeastern Taiwan	Liu *et al.* (1998)
Alopias vulpinus	227.25	0.13	24	-4.8	North Atlantic Ocean	Gervelis and Natanson (2013)
Sphyrna lewini	268.2	0.11	30.5	-1.17	The southern coast of Sinaloa	Anislado-Tolentino *et al.* (2008); Piercy *et al.* (2007)
Sphyrna zygaena	354.9	0.08	21	-7.62	Mexican Pacific	Morán-Villatoro (2018); CMFRI (2016)
Sphyrna mokarran	297.5	0.11	31.4	-2.86	North-western Atlantic and the Gulf of Mexico	Piercy *et al.* (2010); CMFRI (2016)

* Some theoretical maximum lengths were converted from total or furcal length to precaudal length (LPC) based on the linear regression parameters for the species in the study area reported by Carrillo-Colín *et al.* (2022).

Then, Z was calculated by year using the catch curve method through the Chapman-Robson method (1961):

$$Z = -\log(\hat{S}) - \frac{(N-1)(N-2)}{N(T+1)(N+T-1)} \tag{3}$$

Where Z is the total mortality rate, $\hat{S}$ is the survival rate ($\frac{T}{N+T-1}$), N is the total number of sharks observed on the descending limb of the catch curve, and T is the sum of the recorded ages of sharks on the descending limb of the catch curve (i.e., the sum of catch multiplied by recorded age).

Finally, we estimated the exploitation rate (U), defined as the proportion of a population at the beginning of a given period caught during that time (Blackhart; Stanton & Shimada, 2006). This rate was calculated for the fishing season with the equation proposed by Ricker (1975):

$$U = \frac{F}{Z}(1 - e^{-Z}) \tag{4}$$

Where F and Z are the fishing and total mortality rates, respectively.

We used the R-package "FSA" (Ogle *et al.,* 2022) for mortality rate calculations from the statistical software R, vers. 4.0.3 (R Core Team, 2020).

RESULTS

We analyzed 111,206 sharks from 9 species caught in 458 trips made by shark semi-industrial fleets throughout the Mexican Pacific. The overall sex ratio for each species shows a high probability that the proportion is not the expected (1F:1M) since the posterior 95% credible interval of k (degrees of freedom) did not include the value of 1, except for *C. longimanus* and *A. superciliosus* (Table III).

Table III – The Bayesian chi-square analysis results for the sex ratio of oceanic sharks captured by longlines from the Mexican Pacific. The number of female and male samples (F, M), observed ratio, chi-square statistics (X^2), the credible interval of degrees of freedom (K), and probability value that there is not a 1F: 1M sex ratio are shown (P).

Species	F	M	Ratio	X^2	K	P
Prionace glauca	28603	66728	1.0:2.33	15247.04	99.60 (98.52-99.98)	1
Isurus oxyrinchus	2568	3566	1.0:1.38	162.37	96.45 (87.77-99.91)	1
Carcharhinus falciformis	2125	1889	1.0:0.88	13.87	15.69 (6.53-26.48)	0.99
Carcharhinus longimanus	74	56	1.0:0.76	2.49	4.37 (0.87-9.93)	0.86
Alopias superciliosus	721	703	1.0:0.97	0.22	1.56 (0.19-3.98)	0.27
Alopias vulpinus	274	338	1.0:1.23	6.69	8.74 (2.68-17.29)	0.97
Sphyrna lewini	607	366	1.0:0.60	59.69	61.76 (41.15-83.76)	1
Sphyrna zygaena	1322	907	1.0:0.69	77.27	77.29 (55.04-96.80)	1
Sphyrna mokarran	235	124	1.0:0.53	34.32	36.38 (21.14-53.36)	1

Prionace glauca

The precaudal length (PCL) frequency is shown in Figure 2a. Bayesian ANOVA showed decisive evidence of a difference in PCL average size between the sexes (Table IV), where the posterior PCL mean is larger for males with a difference of 1.79 cm (credible interval 95% [$\mathrm{CrI}_{95\%}$] 1.51–2.08). Also, there was decisive evidence of a difference in PCL average size between years (Figure 3a). The blue shark's average natural mortality (M) was 0.215 [confidence interval 95% ($\mathrm{CI}_{95\%}$) 0.17–0.26] for both sexes. In males, the total (Z) and fishing mortality (F) estimates ranged from 0.79–1.13 (mean: 0.95, sd: 0.12) and 0.57–0.91 (mean: 0.73, sd: 0.12), respectively. The exploitation rate (U) shows fluctuations in its trend, with its highest value in 2012 (0.55). For females, Z and F ranged from 0.42–1.70 (mean: 0.82, sd: 0.36) and 0.20–1.48 (mean: 0.60, sd: 0.36), respectively. The exploitation rate shows fluctuations in its trend, with its highest value in 2017 (0.71) (Figure 4a).

Table IV – Two-way Bayesian ANOVA results. We show evidence of the alternative hypothesis regarding the null hypothesis for each factor (sexes and years). F = Female, M = Male, Mean = Mean precaudal length (cm), sd = Standard deviation, BF_{10} = Bayes factor.

Species	Sex	Length range (PCL, cm)	Mean (sd)	BF_{10} Sexes	BF_{10} Years
Prionace glauca	F	33–345	146.37(34.78)	>100	>100
	M	35–325	148.16 (27.60)		

(continuation Table IV)

Species	Sex	Length range(cm)	Mean (sd)	BF_{10} Sexes	BF_{10} Years
Isurus oxyrinchus	F	48.4–273.3	117.63 (19.85)	<1	>100
	M	46.3–259.6	119.70 (19.81)		
Carcharhinus falciformis	F	46–250	130.01 (24.71)	>1	>3
	M	48–271	132.68 (23.01)		
Carcharhinus longimanus	F	60–208	106.29 (22.29)	<0.33	0.33
	M	59.76–179	111.22 (19.76)		
Alopias superciliosus	F	70–218.4	139.67 21.43)	<1	<1
	M	64–235	144.85 (22.28)		
Alopias vulpinus	F	60–230	143.02 (32)	>1	>100
	M	62.5–200	151.78 (22.22)		
Sphyrna lewini	F	20-217	128.54 (34.01)	<0.33	>10
	M	44–215	132.54 (31.61)		
Sphyrna zygaena	F	49–254	132.35 (32.48)	<0.33	>30
	M	40–250	140.90 (34.22)		
Sphyrna mokarran	F	47–233	126.27 (44.95)	<0.33	>1
	M	51–209	129.28 (39.74)		

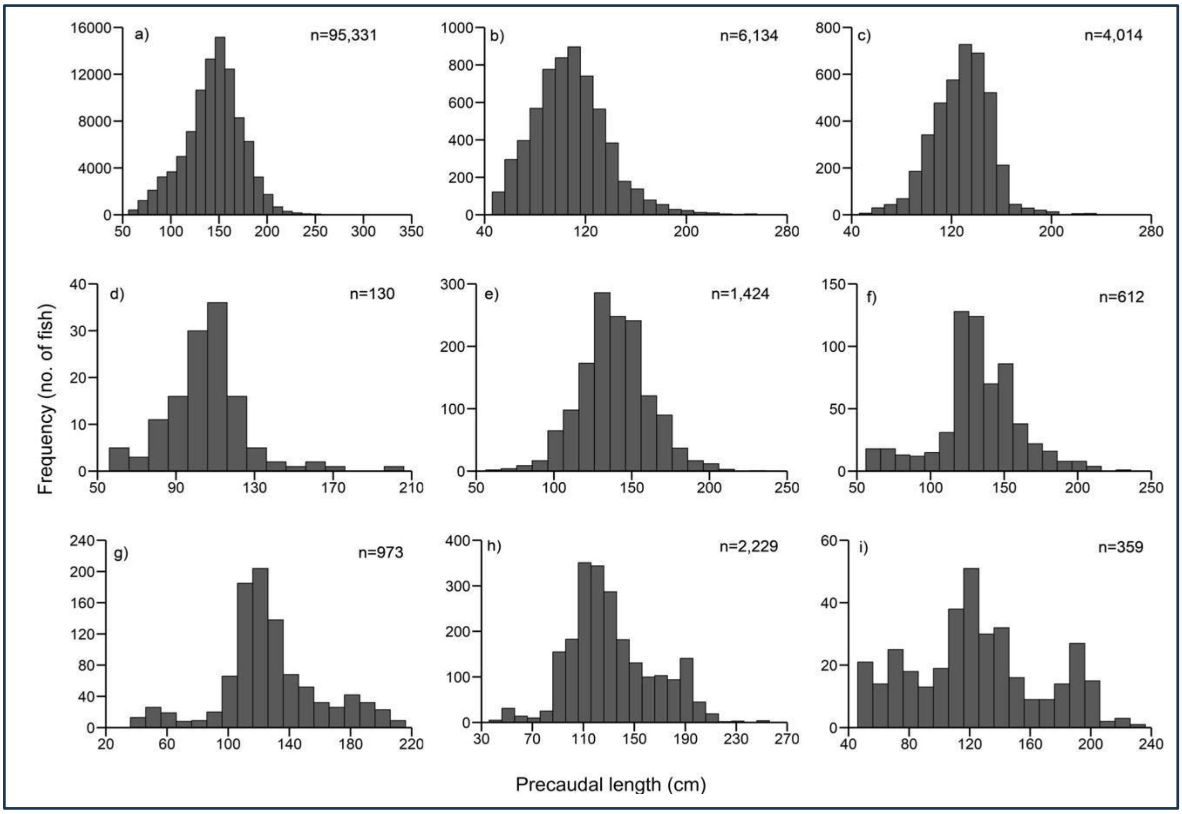
Isurus oxyrinchus

The length-frequency distribution shows a wide range of values (Figure 2b). There was anecdotal evidence supporting the null hypothesis of no difference in size between the sexes, where the posterior PCL mean is larger for males with a difference of 2.10 cm (CrI$_{95\%}$1.07–5.14). We also found decisive evidence of an average size difference between years (Table IV), where the posterior probability distribution of the mean PCL was constant through 2015, decreasing after the year 2016 (Figure 3b). The average M for the shortfin mako shark was 0.202 (CI$_{95\%}$0.153–0.257). Z and F estimates ranged from 0.18–0.43 (mean: 0.30, sd: 0.07) and 0.07–0.32 (mean: 0.19, sd: 0.07), respectively. U shows fluctuations across the time series, with its highest value in 2008 and the lowest in 2018 (Figure 4b).

Carcharhinus falciformis

The size of silky sharks is shown in Figure 2c. We found anecdotal evidence for an average size difference between sexes (Table IV), where the posterior PCL mean is larger for males with a mean difference of 2.66 cm (CrI$_{95\%}$ 1.44–3.88). We found moderate evidence for average size difference between years, where PCL's posterior probability distribution was relatively constant through time (Figure 3c). The M average was 0.21 (CI$_{95\%}$0.167– 0.258), and Z and F ranged between 0.60–1.21 (mean: 0.87, sd: 0.19) and 0.37–0.90 (mean: 0.64, sd: 0.18), respectively. U showed a decreasing trend across the time series (Figure 4c).

Figure 2. Length-frequency distribution of pelagic sharks captured in the northwestern Mexican Pacific between 2006–2018: a) *Prionace glauca*, b) *Isurus oxyrinchus*, c) *Carcharhinus falciformis*, d) *Carcharhinus longimanus*, e) *Alopias superciliosus*, f) *Alopias vulpinus*, g) *Sphyrna lewini*, h) *Sphyrna zygaena*, and i) *Sphyrna mokarran*.



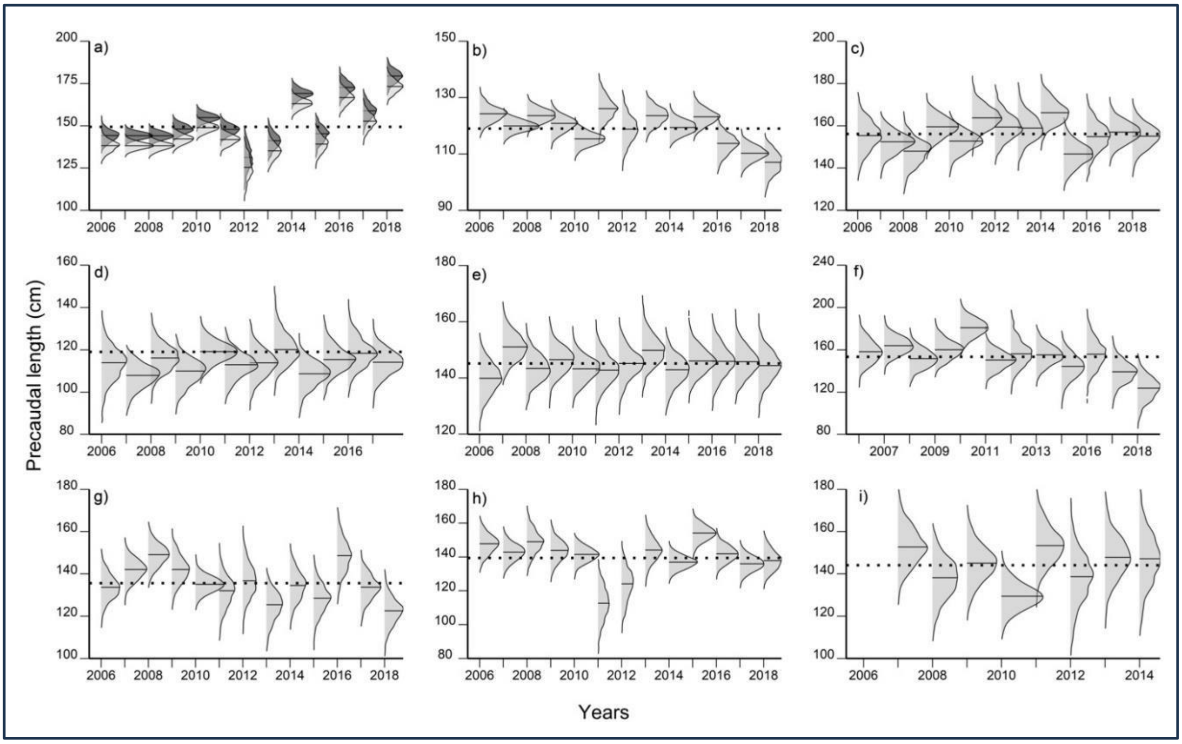
Carcharhinus longimanus

The size is shown in Figure 2d. Moderate evidence supported the null hypothesis of no differences between the sexes (Table IV). The mean posterior probability of PCL was larger in males by 4.92 cm ($CrI_{95\%}$ -1.68–11.55). Also, moderate evidence supported the null hypothesis of no change in PCL between years, indicating that the lengths remain constant through the period (Figure 3d). The M average was 0.175 ($CI_{95\%}$ 0.138–0.213). Z and F ranged between 0.26–0.77 (mean: 0.52, sd: 0.18) and 0.05–0.56 (mean: 0.31, sd: 0.18), respectively. The average of U was 0.23 ($CI_{95\%}$ 0.04–0.39) (Figure 4d).

Alopias superciliosus

The length-frequency distribution is shown in Figure 2e. There was anecdotal evidence supporting the null hypothesis for size difference between the sexes (Table IV), where the posterior mean is larger for males with a mean difference of 5.18 cm ($CrI_{95\%}$ -3.17–7.24). For difference in sizes between years, also we found anecdotal evidence supporting the null hypothesis of no difference in size (Figure 3e). The bigeye thresher has an M, Z, and F of: mean: 0.184, ($CI_{95\%}$ 0.132–0.243); mean: 0.17 (sd: 0.05) and mean: 0.05 (sd: 0.05), respectively. The trends in U show their highest value in 2012 (Figure 4e).

Figure 3. The posteriors distribution of the precaudal length (cm) of pelagic sharks: a) *Prionace glauca*, b) *Isurus oxyrinchus*, c) *Carcharhinus falciformis*, d) *Carcharhinus longimanus*, e) *Alopias superciliosus*, f) *Alopias vulpinus*, g) *Sphyrna lewini*, h) *Sphyrna zygaena*, and i) *Sphyrna mokarran* captured in the northwestern Mexican Pacific during 2006–2018. In panel a) dark grey densities represent females, and light grey represents males. The black dotted lines represent the posterior probability PCL mean for the entire sample, and the horizontal solid line in each distribution represents the mean.



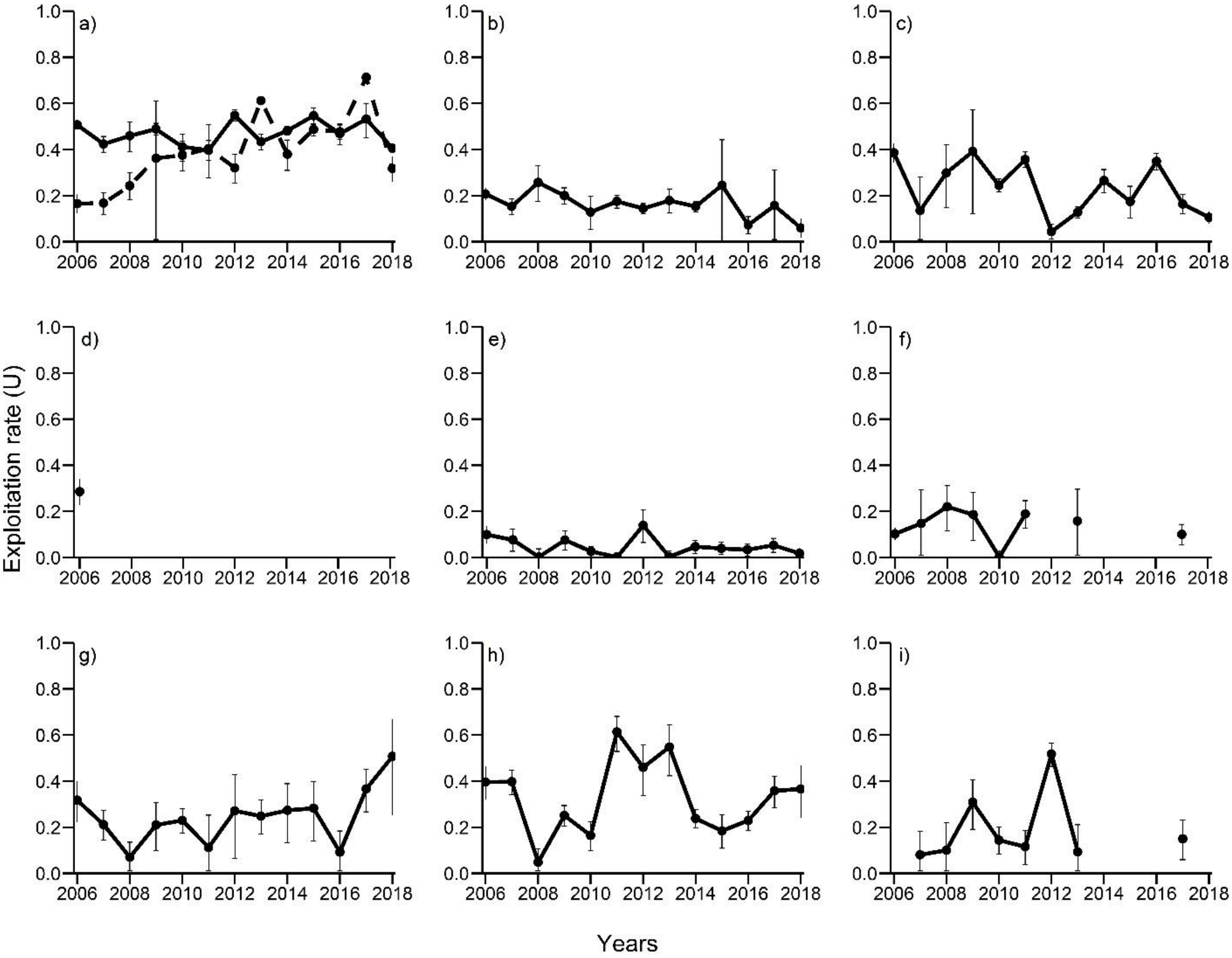
Alopias vulpinus

The length-frequency distribution is shown in Figure 2f. We found anecdotal evidence for differences in average size between sexes (Table IV), where the posterior mean is larger for females with a mean difference of 8.77 cm (CrI$_{95\%}$ 1.24–16.39). We found decisive evidence for differences in average size between years (Figure 3f). The common thresher shark has M, Z, and F mean values: 0.18 (CI$_{95\%}$ 0.142-0.221); 0.27 (sd: 0.08) and 0.16 (sd: 0.08), respectively. The exploitation rate trend is shown in Figure 4f.

Sphyrna lewini

The length-frequency distribution is shown in Figure 2g. There was moderate evidence supporting the null hypothesis of length difference between sexes (Table IV), where males were larger by 4.09 cm (CrI$_{95\%}$ 1.51–6.66) than females. We also found strong evidence of PCL differences between years (Table IV), with fluctuations around the general mean (Figure 3g). The scalloped hammerhead has an average M of 0.176 (CI$_{95\%}$ 0.157-0.192). The Z and F ranged between 0.26–0.97 (mean: 0.50, sd: 0.19) and 0.08-0.79 (mean: 0.32, sd: 0.19), respectively. The U increased in 2017 and 2018 (Figure 4g).

Figure 4.- Exploitation rate of pelagic sharks captured in the northwestern Mexican Pacific between 2006–2018: a) *Prionace glauca*, b) *Isurus oxyrinchus*, c) *Carcharhinus falciformis*, d) *Carcharhinus longimanus*, e) *Alopias superciliosus*, f) *Alopias vulpinus*, g) *Sphyrna lewini*, h) *Sphyrna zygaena*, and i) *Sphyrna mokarran*. In panel a), the solid line represents the males, and the dashed the females. Vertical lines represent a 95% confidence interval.



Sphyrna zygaena

The size-frequency distribution is shown in Figure 2h. We found moderate evidence of no differences in size between sexes (Table IV), where males were larger than females with a mean difference of 8.56 cm (CrI_{95} 6.89–10.23). There was very strong evidence of a difference in PCL between years (Figure 3h). The smooth hammerhead shows an *M* average of 0.185 ($CI_{95\%}$0.132–0.244). The *Z* and *F* ranged from 0.25-1.28 (mean: 0.67, sd: 0.29) and 0.05-1.09 (mean: 0.48, sd: 0.29), respectively. The *U* has fluctuations having the highest values in 2011, 2012, and 2013 (Figure 4h).

Sphyrna mokarran

The size-frequency distribution is shown in Figure 2i. We found moderate evidence for no difference in size between sexes (Table IV), where the males were larger with a difference of 3.01 cm ($CrI_{95\%}$-1.27–7.37). Anecdotal evidence for length differences through the years was found (Figure 3i). The great hammerhead has an average *M* of 0.173 ($CI_{95\%}$0.154–0.190). The *Z* and *F* ranged between 0.26–0.99 (mean: 0.42, sd: 0.25) and 0.09–0.81 (mean: 0.25, sd: 0.25), respectively. The *U* average was 0.19 with a range of 0.08-0.52 (Figure 4i).

DISCUSSION

The sample size problem associated with the statistical significance motivated us to use the Bayesian approach to evaluate the sex ratio and length structure among different factors. The *P*-value in the frequentist approach is sometimes regarded as a measure of effect size so that a small *P* is taken to indicate a large ('significant') effect. However, *P* depends on sample size and effect size, and the result could be significant with large sample size values (Gedorrete, 2011). Furthermore, Bayesian inference results in posterior distributions of a parameter. Thus, it makes a direct probability statement of the parameter of interest (Doll & Jacquemin, 2018); this is why using Bayes factors is proposed as an attractive alternative for hypothesis testing in this study.

Bayesian inference in fisheries management in Mexican waters has not been used often to study chondrichthyan species. Recently, Carrillo-Colín *et al*. (2021) used a Bayesian approach to analyze sizes and estimate age and growth parameters for the golden cownose ray (*Rhinoptera steindachneri*) in the southern Gulf of California. In addition, Bayesian inference has been applied in stock assessments (Cortés *et al*., 2006; ISC, 2017, 2018; Punt *et al*., 2000), modeling life history characteristics (Cortés *et al.,* 2015; Doño *et al*., 2015; Rolim *et al*., 2020).

Information on sex ratio is essential to understanding the relationship between individuals, the environment, and the population's state (Vicentini & Araujo, 2003). However, the sex ratio in the catches may vary from the expected 1:1 from species to species, or even in the same population at different times, influenced by several factors (Vandepuente *et al*., 2012). Our results suggest that the sexual proportion differed from the expected in most species analyzed. These results could result from segregation by sex which is common within adult elasmobranchs (Camhi; Ellen & Elisabeth, 2008). However, sharks have records, such as the shortfin mako (Guerrero-Maldonado, 2002; Ramírez- Gonzáles, 2002) and the oceanic whitetip shark (Strasburg, 1958), that there is no segregation by sex or reproduction stage but by size. Thus, exploiting sharks that exhibit seasonal sex segregation may contribute to a population decline (Mucientes *et al*., 2009). The 90-day shark fishery closure during summer months in Mexican Pacific waters could be helping to reduce the fishing pressure on groups of mature female sharks for some species (Sosa- Nishizaki *et al*., 2020).

Concluding evidence of an overall population bias in sex ratio depends on thorough seasonal and geographical sampling of the total population (Mucientes e*t al*., 2009), as shown in Carrillo-Colín, Castillo-Géniz and Haro Ávalos (2021), using the geographical distribution of the captured species used in the present study. We conclude that the sex ratio bias in our results may be influenced more due to the geographical sampling rather than seasonal distribution because the time scale of the analysis was annual. Therefore, a year-on-year study is needed to determine the seasonal segregation of sexes in the shark fishery in the Mexican Pacific Ocean.

The unimodal distribution of length ranges in the capture highlights the selective nature of the longline used by the Mexican fleet, capturing a specific size range. The exception of this was for the *Sphyrna* species. This could be related to the fact that the principal species of pelagic sharks exploited by these fisheries are the species of the family Alopiidae, shortfin mako, blue shark, as well as silky shark, and oceanic whitetip shark (Márquez-Farías, 2002; Mendizábal y Oriza *et al*., 2002; Soriano-Velasquez *et al*., 2002).

On the other hand, the *Sphyrna* species have coastal-pelagic habits, and *S. mokarran* has been reported as a species regularly caught by various fisheries. However, among the studies of the medium-size fleet fisheries of the Mexican Pacific, it has only been mentioned by Galeana-Villaseñor, Galván-Magaña and Santana-Hernández (2009) in experimental ocean longline fishing (2011) at the entrance to the Gulf of California between 2007-2011.

The longline selectivity depends on the fishing strategy, the seasonality of the trips, the horizontal and vertical distribution of the species, the type and size of the bait, and the size and type of the hook (Santana-Hernández *et al*.,1998). In this study, there are similarities in the length composition of the species depending on the group; for example, the bigeye and common thresher show similar modes among their frequency distribution; the same can be found in the hammerheads only group with the multimodal distribution. The other two species with similar length composition were the silky shark and the shortfin mako. Therefore, it is necessary to study seasonality, spatial variables, depth, and their relation to the species and length composition.

Even with its limitation, the length analysis may help manage the fisheries (Froese *et al*., 2018). The mean size of the blue and smooth hammerhead sharks was smaller in 2012, probably among the few trips with observers on board that year. There has been a trend to larger mean size for the blue shark since 2014, and for the shortfin mako, a trend to smaller mean size since 2016. As with all fishery-dependent length-frequency data, results may be biased due to recruitment variability, gear selectivity, and unrepresentative length measurements for the whole population (Cope & Punt, 2009; Punt *et al*., 2000). Despite the biases mentioned above, the fact that the length frequencies remain stable through the years is a good sign of healthy populations; however, it will be necessary to reinforce these results via applying data-limited approximations to understand the status of the populations better and support the implementation (Sosa-Nishizaki *et al*., 2020).

Although the catch curve analysis is an often-used assessment tool to derive estimates of the instantaneous total mortality (Z) and exploitation rates, our results suggest that the Z estimation does not just reflect natural and fishing mortality rates. This rate might also be influenced by migration processes (emigration and immigration), gear, fishery- dependent aspects, such as gear selectivity (Smith *et al*., 2012; Then *et al.,* 2014), the equilibrium assumptions, and the uncertainty using the inverse von Bertalanffy equation to calculate the ages. Therefore, this method cannot be used to infer information about the stock instantaneous total or fishing mortality rates directly. Still, it allows for comparing the estimations between different years, fisheries, fleets, and estimating exploitation rates. Also, the M estimators from life-history parameters imply uncertainty in the study. Depending on which indirect method for estimating M is used, the estimation of F and U varies, so it is fundamental to choose the best methods. In our case, we used those methods based on longevity, and the von Bertalanffy growth model parameters since several authors mention that they have the best performance (Hamel, 2014; Then *et al*., 2015).

The results showed a high exploitation rate of blue and silky sharks in 2011, which could be overestimated due to the methods for estimating total mortality (Z) values. Therefore, it is essential to be cautious with the results. Several exploitation rates have been estimated for the blue shark, ranging from 0.02 to 0.148 (ICCAT, 2008; Kleiber *et al*., 2009; ISC, 2017). Our mean exploitation rate (0.428) estimation for the blue shark was above this range.

Nevertheless, with our estimations, we can begin to understand the trends in exploiting this species. In the case of the blue shark, male exploitation is constant through time. For the females, it appears to be an increment in the catches.

On the other hand, the overall median of 0.135 exploitation rate in this study is above the global one reported by Worm *et al*. (2013) of 0.06; however, their study has other species with meager exploitation rates. For example, the mean value of the exploitation rate for *S. lewini* of 0.075 is lower than the 0.148 reported by Hayes, Jiao and Cortés (2009) in the Western North Atlantic Ocean and the Gulf of Mexico. For shortfin mako, the mean exploitation rate of this study (0.24) is above of previous estimated rates 0.025-0.028 (Anon, 2017; Byrne *et al*., 2017; Chang & Liu, 2009; ICCAT, 2008; ISC, 2018).

No conclusion can be drawn about the status of the stock in terms of biomass from these analyses. However, our estimates could reflect an approximation of the population's health status, such as the North Pacific stock assessment (ISC, 2017) for the blue and shortfin mako shark (ISC, 2018), which suggest stables populations in North Pacific waters. Nevertheless, Babcock and Nakano (2008), reporting on the International Commission for the Conservation of Atlantic Tunas (ICCAT) bycatch working group's population assessment of shortfin mako, note that populations have declined in both the North and South Atlantic. For the Alopiidae species, the results can only be compared with the stock assessment for the common thresher sharks (Teo *et al*., 2018), concluding that these three species are under-exploited.

There have been few attempts to conduct a stock assessment of silky sharks for the Carcharhinidae species because of limited landings data and the absence of estimates of population sizes. Nevertheless, Bonfil (1990) detected growth overfishing of silky sharks in the Yucatán fishery. In the Gulf of Mexico, Baum and Myers (2004) compared the catch rates of silky sharks from tuna surveys in the 1950s against catch rates from the commercial pelagic longline fishery in the 1990s (targeting tunas, swordfish, and sharks). They found a drop of nearly 91% in silky shark abundance. For the Sphyrnidae species, our *S. lewini* exploitation rate values were below the catches of coastal fishing in Guerrero and Michoacan, Mexico (Anislado-Tolentino, 2008). That could be because this coastal fishery operates near a nursery area, not to mention high catch as shrimp bycatch.

The assessment of the population status of pelagic sharks is hampered by the generally poor data quality associated with bycatch species in longline fisheries and problems with CPUE standardization. Hence it is difficult to determine the degree of fishing pressure experienced by these species and whether current fishing rates are sustainable. However, due to the high complexity of applying stock assessment models, length analysis can be an initial indicator of the condition of stocks. Our results indicate that some shark populations exploited in the North and Central Mexican Pacific are at low levels of exploitation; nevertheless, it is necessary to continue with robust analysis (catch standardization or demographic analysis) to have a broader picture.

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