EXPLORING THE USE OF LENGTH BASED INDICATORS FOR BLUE SHARK IN THE INDIAN OCEAN

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SUMMARY

Blue shark (Prionace glauca) is the pelagic sharks most frequently captured in pelagic fisheries. It is considered one of the main shark species in tuna-RFMOs worldwide, and the species for which more data is available, including size distribution data. This paper presents an alternative method for providing a snapshot assessment of status, with the development of length based indicators (LBI) and comparison to reference points derived from life-history and ecological theory. The data used came from the last IOTC blue shark stock assessment carried out in 2017. This exploratory analysis revealed some differences between fleets over different components of the stock, but in general met the indicators expectations with the stock being considered in "good" status according to most of the reference points. There were some inconsistent results across different data sources, indicating that issues of gear selectivity and/or differences in the spatial distribution of the fleets in relation to various components of the stock may be influencing the LBI. There is the need for further interpretation of the data in relation to the fishery and spatial structure of the stock, as well as more work directed to determine the appropriateness of the use of those reference points for elasmobranchs, taking into account that they were derived mostly for teleost and shellfish stocks. However, and even thought this is a preliminary exercise at this point, we hope that it provides additional useful information for the advancement of the blue shark management and conservation in the Indian Ocean.

KEYWORDS: Blue shark, data-limited, Indian Ocean, length based indicators (LBI), pelagic fisheries.

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1. Introduction

Blue shark (*Prionace glauca*) is one of the pelagic shark species most frequently caught as bycatch of pelagic fisheries all over the world, sometimes as targeted species. It is considered one of the main shark species in tuna-RFMOs worldwide. In the Atlantic and Indian Oceans, from the previously conducted ERAs, blue shark received a high vulnerability ranking as it was estimated as one of the most productive shark species, but was also characterized by a high susceptibility to longline gear (Cortés et al., 2015; Murua et al., 2012), while in the Pacific it was found to be one of the most vulnerable species to pelagic longliners.

Blue shark is most likely the pelagic elasmobranch species for which more data is currently available, including biological data, recent reported catch, discard data and length composition data. Particularly, an extensive review of the Atlantic and Indian Ocean size composition was performed using detailed observer data (Coelho et al., 2018). However, there are still considerable uncertainties in the reported historical catch data and discard rates for this species.

For the Indian Ocean blue shark, a first stock assessment was attempted in 2015; however due to uncertainties in the input data it was not possible to provide stock status. A new assessment was performed in 2017 by the IOTC Working Party on Ecosystems and Bycatch (WPEB) with improved data. Four stock assessment models were applied in 2017, specifically a data-limited catch only model (SRA), two Bayesian biomass dynamic models (JABBA with process error and a Pella-Tomlinson production model without process error) and an integrated age-structured model (SS3). All models produced similar results suggesting the stock is currently not overfished nor subject to overfishing, but with the trajectories showing consistent trends towards the overfished and subject to overfishing quadrant of the Kobe plot. The major sources of uncertainties identified were catches and CPUE indices of abundance (IOTC, 2017).

Even though blue shark has recently been assessed using quantitative methods on all oceans, using mostly integrated age-structure models, some models remain highly uncertain due to uncertainties and conflicts in the input parameters. Therefore, since a considerable number of the required pieces of information is already available (mainly catch series, relative indices of abundance and size distributions), one possible alternative next step in the short/medium term for the assessment of the species could rely on providing alternative indicators from other sources, such as the case of length based indicators (LBI). Therefore, the objective of this paper is to develop and present length base indicators, from length-frequency distribution and compare those o reference points derived from life-history parameters and ecological theory or empirical observation, providing a snapshot assessment of status.

2. Material and methods

2.1. Length based indicators

There has been increasing interest in the application of length-based indicators (LBI) for data-limited stocks. Size-frequency data are often available for both exploited species and common bycatch species. Size-frequency data can be used for screening methods and potentially developing reference points and indicators that reflect size-selective fishing pressure (ICES, 2015a). Indicators of status are calculated from length-frequency distributions and compared to Reference Points (RP) derived from life-history parameters and ecological theory or empirical observation, providing a snapshot assessment of status under steady state assumptions.

The ICES workshop on the 'Development of Quantitative Assessment Methodologies based on Life-history Traits, Exploitation Characteristics and other Relevant Parameters for Data-limited Stocks' (WKLIFE V) selected a set of LBIs characterising conservation of large and small individuals, yield optimisation and maximum sustainable yield (ICES, 2015a). A traffic light approach was used to compare ratios of indicators and reference points to expected values where conservation, yield or MSY properties were considered as achieved. This suite of LBI outputs is considered to provide an overall perception of stock status.

The underlying data requirements are:

- Length at 50% maturity L50%
- von Bertalanffy growth parameter L∞
- Maximum length Lmax (whilst this parameter is not used per se, this parameter can be used to estimate L∞ (if otherwise unavailable) or to help evaluate what may be a sensible value of L∞ in published growth studies)
- Life history invariant M/k or individual estimates of natural mortality M and von Bertalanffy k
- Length-weight conversion factors a and b
- Catch at length (by sex where appropriate)

The LBI considered by ICES (**Table 1**), arranged by property, are:

Conservation of large individuals: Comparing indicators characterising the upper portion of the length frequency distribution to the RP L∞ provides an indication of the degree of truncation of the population size structure that may be caused by fishing. Indicators chosen to characterise the upper portion are the mean length of the largest 5% (Lmax5%) and the 95th percentile (L95%) of the length frequency distribution, both of which are considered more stable than the maximum length in the catch (ICES, 2014; Probst et al., 2013). The ratio of indicator to RP L∞ is expected to be above 0.8, based on a simulation study (Miethe & Dobby, 2015).

The proportion of mega-spawners (fish larger than the optimum length plus 10%) in the stock (Pmega) follows the principle of 'Let the mega-spawners live' (Froese, 2004). Old, large fish play several important roles in the long-term survival of a population, as they may produce more eggs (increased fecundity), larger eggs or young (which may have better survival) and may have a greater spawning success. Consequently, Pmega can be viewed as a simple proxy for the resilience of a stock. The principle is to implement a fishing strategy where no mega-spawners are caught. However, if the catch reflects the size structure of the population, values above 0.3 are considered healthy (Froese, 2004; Miethe & Dobby, 2015).

Conservation of immatures: LBI relating to small individuals follow the principle 'Let them spawn' (Froese, 2004). Overfishing is theoretically impossible if every spawner produces at least one replacement spawner (Myers and Mertz, 1998); therefore, if the indicator length at first capture (Lc; estimated as the length at 50% of the first mode) is above the RP Lmat, biomass is likely to be above that which produces MSY (ICES, 2014). A simulation study found the 25th percentile (L25%) of the length frequency distribution to be a suitable proxy when Lc is difficult to estimate (Miethe & Dobby, 2015). Based on theory, the ratio of indicator to RP Lmat is expected to be greater than 1.

Optimal yield: LBI relating to optimal yield follow the principle 'Let them grow' (Froese, 2004) which states that all fish caught should be within 10% of the RP optimum harvest length (Lopt). Lopt represents the length where cohort biomass and egg production are maximal in an unexploited state and where catch is maximal for a given fishing mortality (F), or F minimal for a given catch (Cope & Punt, 2009). Lopt is calculated:

$$L_{opt} = \frac{3}{3 + {M}/{k}} L_{\infty}$$

Where M is natural mortality, k is the von Bertalanffy rate coefficient and M/k is a life history invariant. If the central indicators mean length of individuals larger than Lc (Lmean) or length class with maximal biomass (Lmaxy) are close to the RP Lopt then either the stock is lightly exploited or the fishery is operating with a target length that is sustainable and close to MSY (ICES, 2014). Given the requirement that fish caught are within 10% of Lopt, the ratio of indicator to RP should be 0.9–1.1.

MSY: F=M is a proxy for MSY. The length at which F=M (LF=M) is rearranged from Beverton and Holts equation for mean length in the catch as a function of the von Bertalanffy growth parameters, length at first capture and natural and fishing mortality:

$$L_{F=M} = (1 - a)L_c + aL_{\infty}$$

$$a = \frac{1}{2\left({M}/{k}\right) + 1}$$

This RP gives the mean length in the catch expected from fishing at F=M in the long term; hence a suitable indicator is Lmean. If Lmean is less than LF=M then fishing mortality is likely to be larger than M and hence FMSY (ICES, 2014). The ratio of indicator to RP should therefore be greater than or equal to 1.

Table 1: Summary of length-based indicators (LBI) with corresponding reference points and indicator ratio (* = simplified equations resulting from substituting M/k = 1.5; an assumption based on the life history of teleost fish).

Indicator	Calculation	Reference point	Indicator ratio	Expected value
$L_{max5\%}$	Mean length of largest 5%	L_{inf}	$L_{max5\%}/L_{inf}$	> 0.8
$L_{95\%}$	95th percentile	L_{inf}	$L_{95\%}/L_{inf}$	> 0.8
P_{mega}	Proportion of individuals above Lopt + 10%	0.3-0.4	P_{mega}	> 0.3
$L_{25\%}$	25th percentile	L_{mat}	$L_{25\%}/L_{mat}$	> 1
L_c	Length at first catch (length at 50% of mode)	L_{mat}	L_c/L_{mat}	> 1
L_{mean}	Mean length of individuals > Lc	$L_{opt}=2/3L_{inf}$ *	L_{mean}/L_{opt}	≈ 1
L_{maxy}	Length class with maximum biomass in catch	$L_{opt}=2/3L_{inf}$ *	L_{maxy}/L_{opt}	≈ 1
L_{mean}	Mean length of individuals > L_c	$LF=M=(0.75Lc+0.25L_{inf})$ *	$L_{mean}/LF=M$	≥ 1

Whilst such length-based approaches have been used for various stocks of teleost and shellfish (ICES, 2015b), they have not been applied extensively to elasmobranchs. Potential obstacles for using LBI for elasmobranchs include:

- *Sample size*: Are the underlying sample sizes sufficiently large, given that there can be a broad length range and limited availability of data?
- *Variability in measurements*: Elasmobranchs may be measured as total length (with caudal fin depressed), total length (with caudal fin in natural position), fork length, precaudal length or, for batoids, disc width. Furthermore, some measurements may be taken in a 'straight line' under the body or by tape measure over the body, the latter potentially including 'curvature' and thus exaggerating true length.
- *Sexual and ontogenetic segregation*: The complex segregation of many shark species, whereby they can aggregate according to sex and/or size, may influence the catches that are measured, and so could confound any observations on temporal changes in LBI. This issue may also be more pronounced when sampling effort (e.g. numbers of trips) are limited.
- *Size selectivity*: Some fisheries encountering sharks may not sample the full length range, as smaller individuals may not get hooked, larger individuals may break through the snood. Hence, any spatio-temporal changes in fishing

practices and gear configurations may result in a change in size selection, which may not be accounted for in underlying data.

2.1.1. Length-length conversion factors

As the various data considered in the present case study incorporated information on total length (LT), fork length (LF) and precaudal length (LPC), attempts have been made to standardise all data to LT, using the equations below.

LPC = 0.762.LT – 0.2505: Nakano et al. (1985), cited by Semba & Yokoi (2016)

LPC = 0.76.LT – 1.95 : McKinnell & Seki (1998), cited by Nakano & Seki (2003)

LPC = 0.74.LT + 3.92: Hazin et al. (1991), cited by Nakano & Seki (2003)

LF = 1.3908 + 0.8313.LT: Kohler et al. (1996)

Conversions of LPC to LT were based on the mean values obtained from equations 1–3. Only a single equation was used for LF to LT (Kohler et al., 1996), as this study was based on a much larger sample size than other published studies.

2.1.2. Maximum length Lmax

The maximum length reported for *P. glauca* is at least 383 cm LT (Bigelow and Schroeder, 1948; Ebert & Stehmann, 2013). Interestingly, the largest length bin in the data set analysed was the 365–370 cm LF (= 437.4–443.4 cm LT), which would indicate that either the Lmax in several sources is incorrect, there has been a measurement or input error, or some of the data ascribed as LF were actually LT.

Whilst Lmax is not necessarily included within LBI, it is recommended that such information be collated, as Lmax can be used to derive estimates of L∞ (if robust growth studies are lacking), it can be informative as to gauging whether published growth parameters are biologically plausible, and it can help in the quality checking of input data.

2.1.3. Length at 50% maturity L50%

This was based on the reported lengths at 50% maturity (L50%) for female *P. glauca*. Published estimates of L50% range from 193 cm LT (Joung et al., 2011; cited by Rice & Semba, 2014) and 194.4 cm LT (Jolly et al., 2013), to 159 cm LPC (=210 cm LT; Nakano et al. 1985) and 140–160 cm LPC (= 186–212 cm LT; Nakano & Seki, 2003).

For the purposes of the present study, two values of L50% were considered. The first value (193.7 cm LT) was based on the mean of the estimates of Joung et al. (2011) and Jolly et al. (2013), and includes one study from South African waters. This value was broadly comparable with the findings of Francis & Duffy (2005). The second value was 210 cm LT, as this better reflected the findings of Nakano et al. (1985) and Nakano & Seki (2003), noting that these studies were from the north-western Pacific Ocean.

2.1.4. Growth parameters L∞ and k

There have been several age and growth studies for blue shark in the Pacific Ocean and around South Africa (Cailliet & Bedford, 1983; Tanaka, 1984; Nakano, 1994; Hsu et al., 2011; Jolly et al., 2013; Fujinami et al., 2016) and so there are various estimates for both k and L∞. The values considered in the present case study are given in **Table 2**. Given that the female L∞ estimated by Cailliet & Bedford (1983) does not appear to be biologically plausible, and the estimate of k was much higher than other studies, this study was excluded.

From the remaining five studies, the mean value of k for females was 0.138 (range = 0.11–0.172), whilst the mean value of L∞ for females was 330.4 cm LT (range = 317.4–339.2).

Table 2. Summarised growth parameters considered in the exploratory analyses. F = Female; M = Male; C = Combined; LT = Total length (cm); LPC = Pre-caudal length (cm).

Area	Sex	Length	L_∞	Conversion to L_T	*K*	Source
California	F	L_T	241.9		0.251	Cailliet & Bedford (1983)
	M	L_T	295.3		0.175	
	C	L_T	265.5		0.223	
North Pacific	F	L_{PC}	243.3	(= 321.9 L_T)	0.144	Nakano (1994), cited by Semba & Yokoi (2016)
	M	L_{PC}	289.7	(= 383.5 L_T)	0.129	
North Pacific	F	L_T	317.4		0.172	Hsu et al. (2011), cited by Semba & Yokoi (2016)
	M	L_T	375.8		0.121	
North Pacific	F	L_{PC}	256.3	(= 339.2 L_T)	0.147	Fujinami et al. (2016), cited by Semba & Yokoi (2016)
	M	L_{PC}	284.8	(= 377.0 L_T)	0.117	
North Pacific	F	L_{PC}	256.1	(= 338.9 L_T)	0.116	Tanaka (1984), cited by Nakano & Seki (2003)
	M	L_{PC}	308.2	(= 408.0 L_T)	0.094	
South Africa	F	L_T	334.7		0.11	Jolly et al. (2013)
	M	L_T	294.6		0.14	
	C	L_T	311.6		0.12	

2.1.5. Natural mortality M

There have been several studies attempting to estimate M for *P. glauca*. Aires-da-Silva & Gallucci (2007) estimated annual survivorship (s), where s = e–M, for the North

Atlantic stock from various theoretical approaches. The mean and median survivorships for ages 2+ were estimated at 0.78 and 0.81, and the maximum estimated survivorship was 0.91. These three values equate with estimated values of M of 0.248, 0.211 and 0.094, respectively.

Biologically-speaking, M should be age/size dependent, with higher M for the smallest size classes. Semba & Yokoi (2016) provided age- and sex-specific estimates of M for *P. glauca* in the North Pacific. Depending on the estimator and growth parameters used, estimates of M ranged from 0.081–0.392 (males) and 0.083–0.365 (females). The means of these values were approximately 0.2.

For the purposes of the present study, two arbitrary values of M were considered: 0.1 (which is close to the minimal estimates of both Semba & Yokoi (2016) and Aires-da-Silva & Gallucci (2007)), and 0.2, which was the approximate mean value of Semba & Yokoi (2016) and close to the median value of Aires-da-Silva & Gallucci (2007).

The life history parameters used for the exploratory analyses of LBI for Indian Ocean blue shark are summarised in **Table 3**.

Table 3. Summary table of input parameters for LBI.

Parameter		Value (L_T)	Value (L_F)
L_∞ (female)	Mean	330.4 cm	276.05
	Min	317.4 cm	265.25
	Max	339.2 cm	283.37
$L_{50\%}$ (female)	Lower estimate	193.7 cm	162.41
	Upper estimate	210 cm	175.96
k (female)	Mean	0.138	
	Min	0.110	
	Max	0.172	
M	Lower estimate	0.1	
	Upper estimate	0.2	
a			3.18×10^{-6}
b			3.1313

2.2. Data availability

Data used during the last stock assessment by IOTC were used for exploratory analyses of LBI. Sex-disaggregated size data were available for five ‘fleets’ operating, or that had operated, in the IOTC area (**Table 4**).

Data from the former Soviet Union were available for the years 1966–1989, but sample sizes could be small in many of these years. Consequently, data were aggregated into three 8-year time blocks (1966–1973, 1974–1981 and 1982–1989).

There were a few records (n = 11) of fish in or above the [335–340) length bins. If these values do reflect LF then that would equate with specimens greater than 4 m LT, and so further quality checks on whether these are coding errors, or whether the original data actually refer to LT could usefully be undertaken. For the exploratory studies presented here, all fish in or above the [340-345) length bins were excluded.

Table 4: Sample sizes and length ranges of Indian Ocean blue shark measured in Japanese, Portuguese, Taiwanese and South African fisheries, with earlier data from former Soviet Union exploratory fisheries.

Nation	Years	Females		Males	
		Sample size (by year)	Length range	Sample size (by year)	Length range
Japan	1992–2013	146–2571	[40–45) – [285–290)	69–2337	[40–45) – [365–370)
Portugal	2011–2014	83–358	[100–105) – [290–295)	462–1980	[95–100) – [295–300)
Taiwan	2004–2013	157–898	[55–60) – [350–355)	124–1199	[55–60) – [345–350)
Soviet Union	1966–1989	2–324	[60–65) – [605–310)	1–597	[55–60) – [310–315)
South Africa	2012–2014	200–528	[70–75)– [320–325)	733 – 1311	[70–75) – [310–315)

2.3. Data analyses

The following analyses were undertaken

- Initial analyses of Portuguese data to look at various scenarios (e.g. using different life history parameters) to inform on base case by sex and combined sexes
- Examination of USSR (1966-1973; 1974–1981; 1982–1989 time blocks) and Japanese data (1992–2013, by year), to see if there were any longer-term changes (noting that there may be gear-related and spatial factors as well as temporal changes)
- Japanese data: This dataset provided the best temporal resolution for recent trends by sex and sexes combined
- Nation or fleet-related differences: Analyses of Japanese (2009–2013; subset comparable to other nations), Portuguese (2011-2014; only 4-yr available), Taiwanese (2009–2013; 5-yrs of better data), and South African data (2012–2014; only 3-yr available). Analyses was also conducted to see if LBI varied between fisheries over a relatively consistent period by sex and combined.

3. Results

3.1. Exploratory analysis of Portuguese data and selection of parameters

Assuming an M/K ratio of 1.5, indicators examining the effects of fishing on large individuals show all components of the stock (males, females and combined) to be doing quite well regardless of the value of L∞, with few indicator ratios shifting from good to poor status when increasing L∞ to its maximum value. Increasing L∞ increased the optimal yield and MSY reference points, but made no difference to MSY traffic light status and little difference to optimal yield, with just a few shifts from poor to good when considering the mean length of individuals (**Table 5**).

Given the minor effect increasing L∞ had on this stock, the maximum value of L∞ = 283.37 cm was adopted for the rest of the analyses. This is the most precautionary value and consistent with observed data.

The ratios of Lc and L25% to Lmat were close to the expected value of 1, so indicators for this stock will be sensitive to the value of Lmat chosen. Here the minimum value of Lmat = 162.41 cm was selected, which is most relevant for the Indian Ocean.

Both optimal yield Lopt and MSY LF=M reference points were sensitive to the ratio M/K, as is the indicator Pmega, which is calculated from Lopt. Decreasing M/K resulted in a more pessimistic assessment in terms of mega-spawners, with all components of the stock classified as poor when using the lowest value (0.58), and MSY. Subsequent analyses used the mean value of M/k = 1.45.

Table 5. Summary of LBI using the selected life history parameters. Cells in green indicate those indicators that are above the expected value (see **Table 1**) and theoretically represent ‘good’ status.

Males

Year	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
2011	0.97	0.94	0.66	1.24	1.18	1.21	1.29	1.07
2012	0.95	0.92	0.28	1	0.94	1.03	1.27	1.06
2013	0.96	0.92	0.45	1.03	0.91	1.09	1.32	1.14
2014	0.93	0.91	0.32	0.97	0.87	1.02	1.29	1.09

Females

Year	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
2011	0.94	0.91	0.74	1.27	1.31	1.23	1.27	1.02
2012	0.95	0.92	0.51	1.15	1.12	1.13	1.24	1.04
2013	0.94	0.91	0.39	1.09	1.06	1.08	0.93	1.03
2014	0.82	0.77	0.1	1.06	1.03	0.98	0.93	0.95

Both sexes

Year	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
2011	0.97	0.94	0.67	1.24	1.15	1.2	1.27	1.08
2012	0.95	0.92	0.35	1.06	0.94	1.06	1.27	1.09

2013	0.95	0.92	0.44	1.06	0.91	1.08	1.32	1.14
2014	0.93	0.91	0.29	1	0.87	1.01	1.29	1.08

3.2. Exploratory analysis of longer-term trends in LBI from Soviet Union (1966–1989) and Japanese (1992–2009) fleets

Analyses of Soviet Union data (sexes combined, **Figure 1**) for 1966–1989 revealed a healthy presence of large individuals and showed the stock to have been fished sustainably according to MSY. Lc and L25% decreased over the time series, indicating more fish being captured before reaching maturity. Lc fell below its expected value in 1974–1981, and L25% in 1982–1989. Lmaxy was above Lopt throughout the time-series, indicating targeting of fish above the optimum length, while Lmean decreased in relation to Lopt, indicating a shift towards smaller fish.

Analyses of Japanese data from 1992–2009 (**Figure 2**) showed few large individuals, with an increase towards- or obtained- expected levels from 2008 onwards. Pmega was close to zero most years and both indicators relating to the conservation of small individuals fell well below Lmat throughout the time series, showing an increase from 2007. The indicator ratio for MSY fluctuated close to, but mostly below, 1.

The longer-term shift from good to poor conservation status of large and small individuals, and drop in MSY indicator ratio values is likely due to differing selectivities between the Soviet Union and Japanese fleets rather than a longer-term change in population dynamics. This is supported by the Lmaxy and Lmean indicators falling below Lopt, indicating targeting of fish below the optimum length by the Japanese fleet.

3.3. Exploratory analysis of LBI derived from Japanese length-frequency data

Analyses of Japanese data (1992–2013) showed indicators for the conservation of large individuals to generally be lower and more stable for females than males (**Figure 3** and **Figure 4**). Although a slight increase in these indicator values was observed for males, the increase in combined sex status of large individuals from 2008 appeared to be driven by the female component.

Pmega was zero for females until 2003, and less than 0.1 for both sexes throughout most of the time-series. Contrarily, L25%, which focuses on the conservation of small individuals, was generally higher for females than males, but both indicators relating to immatures fell below Lmat for both sexes throughout the time-series. The increase in L25% from 2007 was slightly more prominent for males.

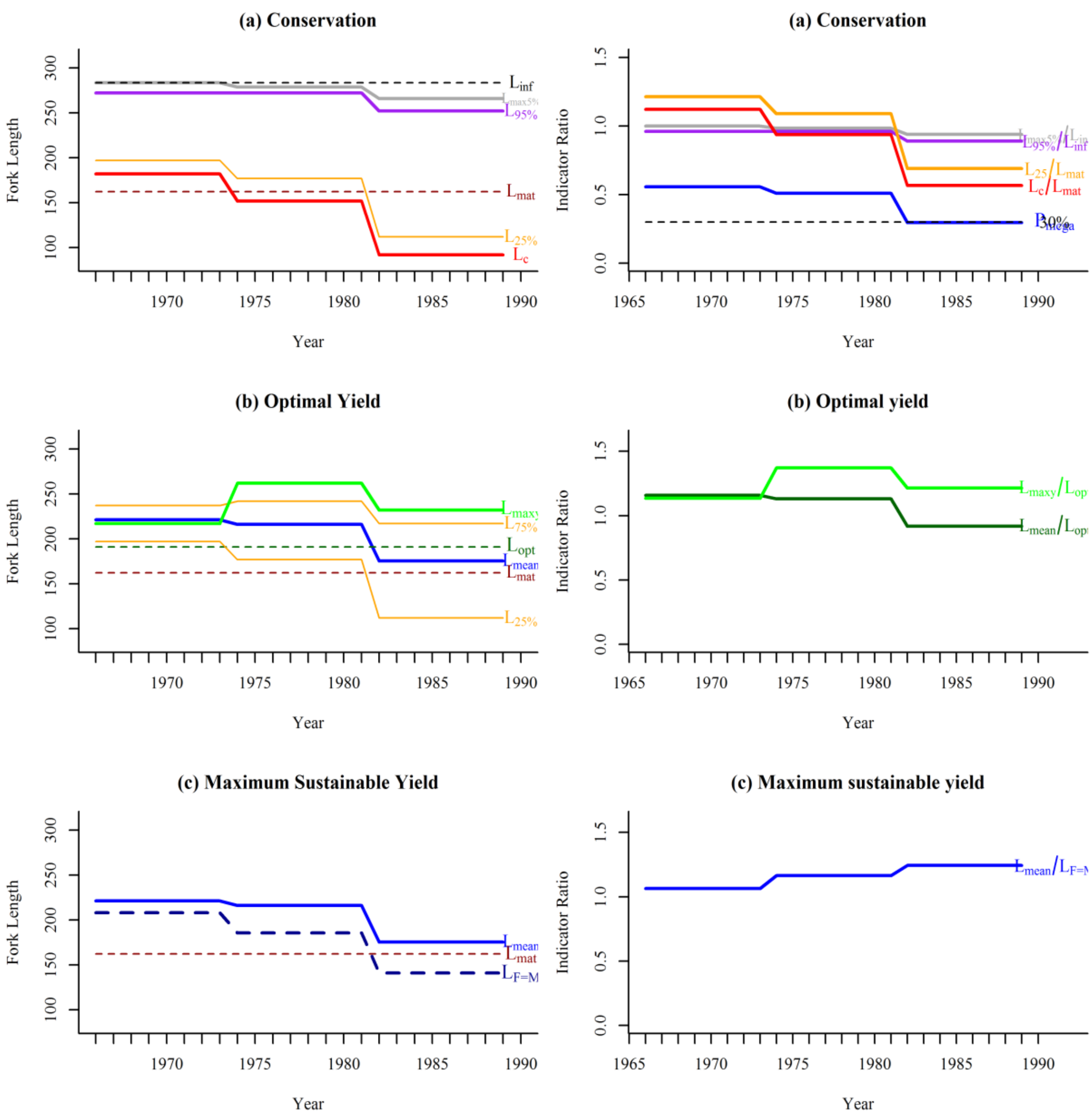

Figure 1. Length based indicators for Indian Ocean blue shark by time period (length data from USSR exploratory fleet).

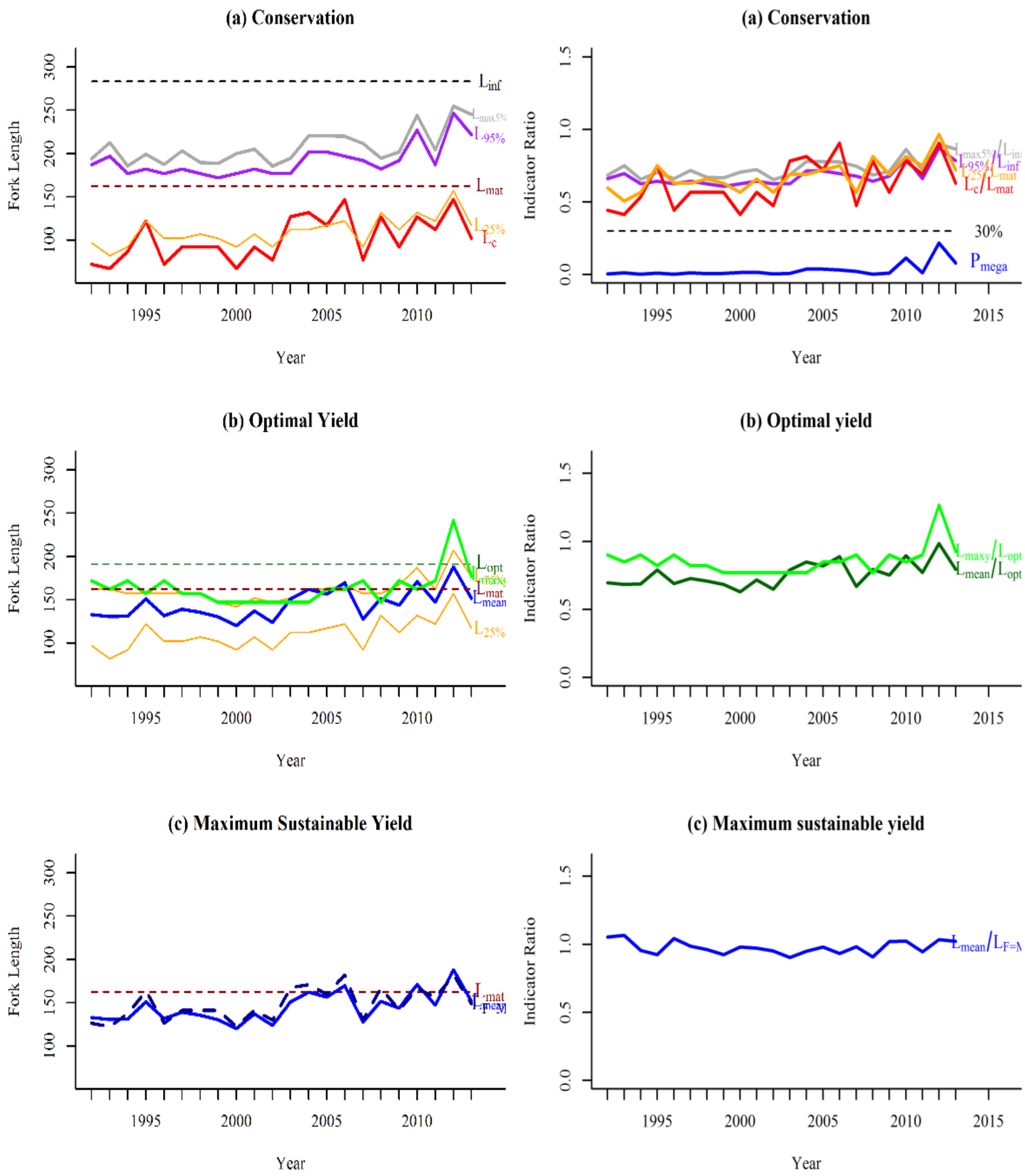

Figure 2. Length based indicators for Indian Ocean blue shark by year (length data from Japanese fleet).

The indicator Lmaxy showed a pronounced decrease prior to 1998 and increased from then onwards for males and, to a much lesser extent, females and combined sexes. A shift towards larger individuals was also indicated by Lmean from 2000, although both indicators remained at or below Lopt for most of the time series. The indicator ratio for MSY fluctuated close to 1 though most of the time series.

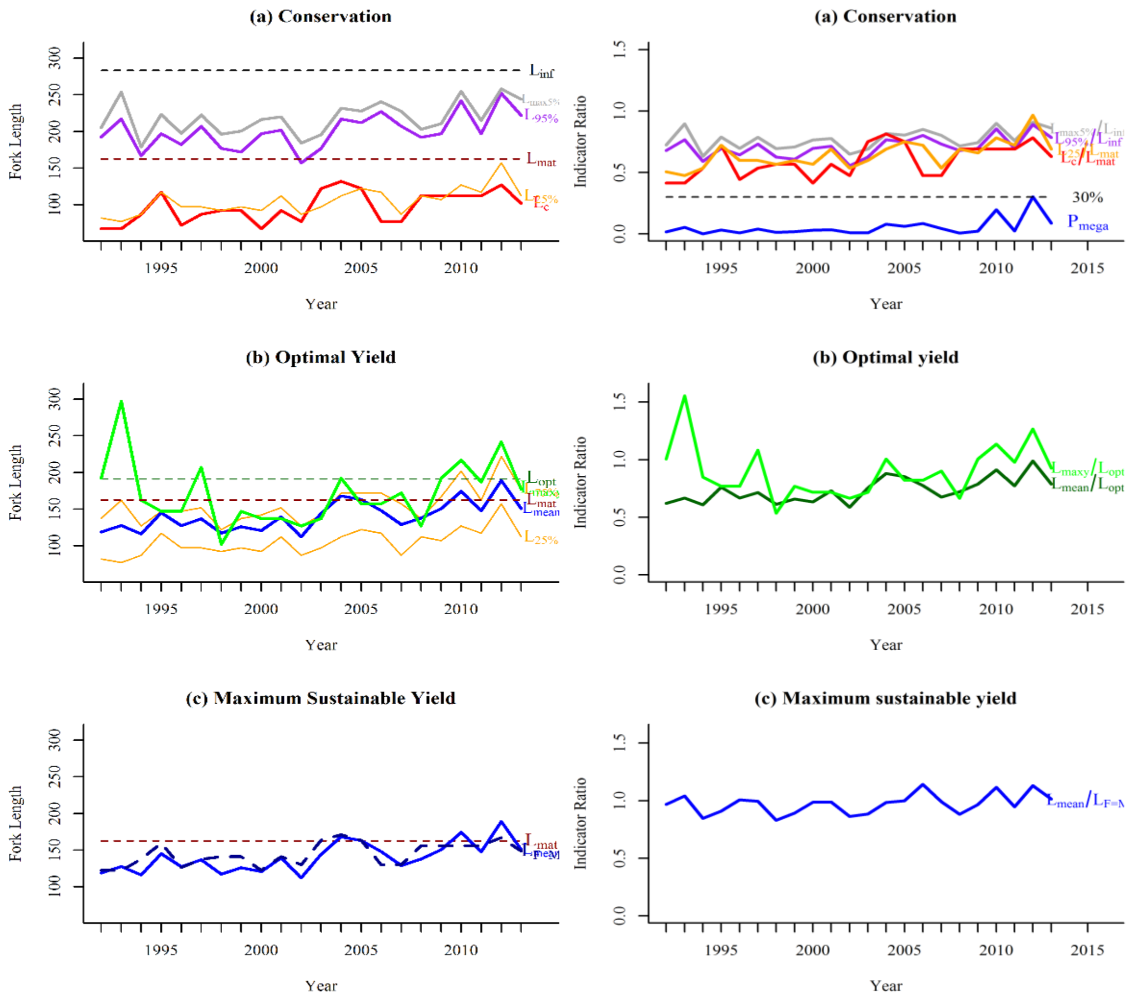

Figure 3. Indicators, reference points and indicator ratios for male blue shark in the Indian Ocean by year (length data from Japanese fleet).

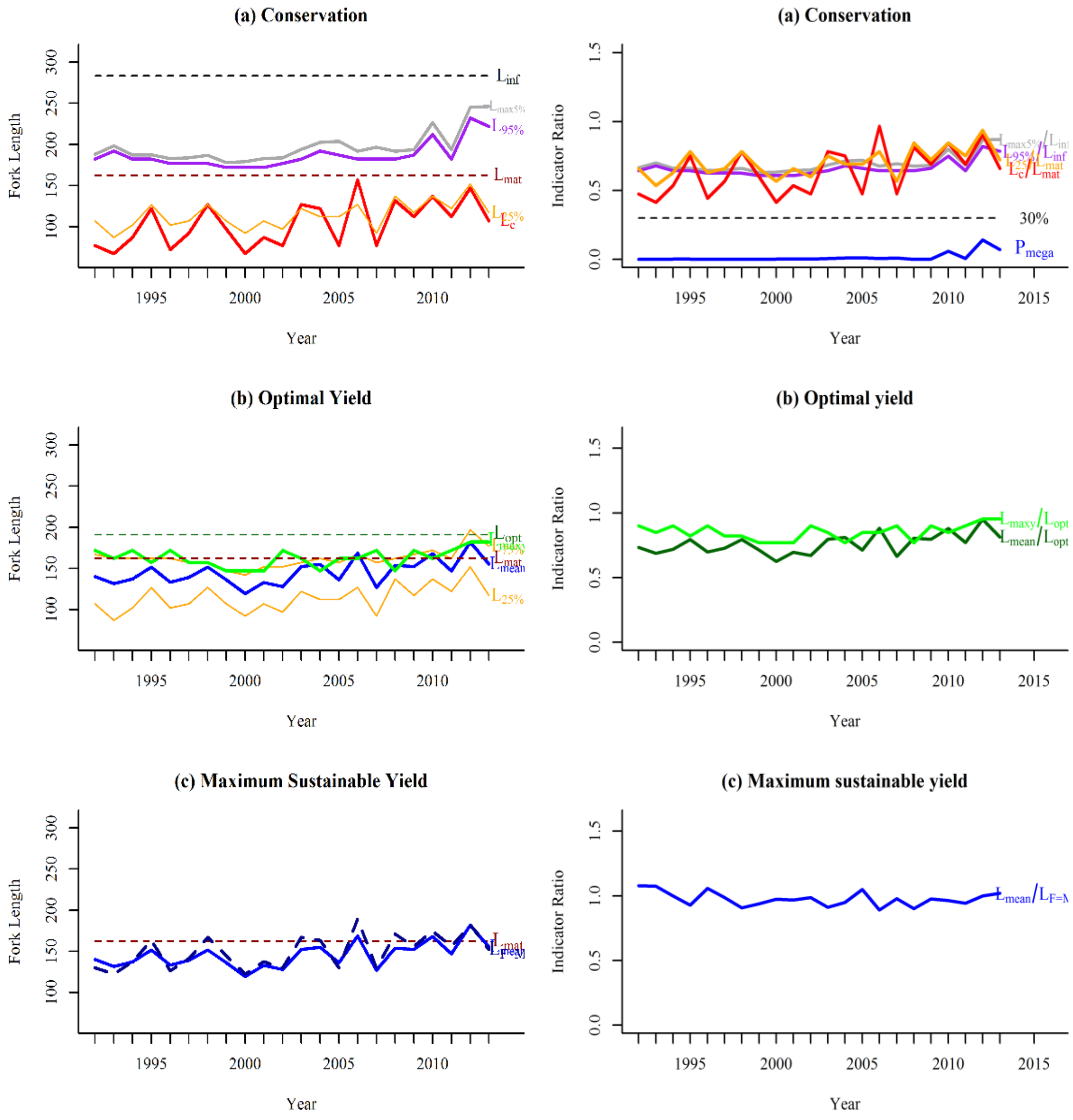

Figure 4. Indicators, reference points and indicator ratios for female blue shark in the Indian Ocean by year (length data from Japanese fleet).

3.4. Exploratory analysis of LBI from different fleets

Analyses of data from four countries over a relatively consistent period (**Table 6**; **Figure 5**) revealed some differences in status between fleets over different components of the stock. Indicator ratios focusing on the conservation of large and small individuals (excluding Lc/Lmat) were generally below expected values for Japan, except Lmax5% for males, while other nations met expectations, except for South Africa where Pmega for males was less than 0.3. Lc was below or equal to Lmat for all nations when considering males and for Japan and South Africa when considering females. Optimal yield indicators from Japanese data suggested that fishing was at or below Lopt, while data from other nations suggesting that fishing was at or above Lopt. These differences in selectivity were also indicated by length frequency distributions. All nations met MSY except Japan when considering females or both sexes combined.

Table 6. Summary of LBI using the selected life history parameters. Cells in green indicate those indicators that are at or above the expected value and theoretically represent ‘good’ status.

Males	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
Japan	0.86	0.78	0.08	0.72	0.69	0.82	0.98	1.01
Portugal	0.96	0.94	0.5	1.09	0.94	1.12	1.29	1.15
Taiwan	0.98	0.91	0.35	1.06	0.97	1.07	1.11	1.08
South Africa	0.94	0.89	0.26	1.06	1	1.04	1.01	1.03

Females	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
Japan	0.76	0.68	0.02	0.75	0.69	0.8	0.9	0.98
Portugal	0.94	0.91	0.52	1.12	1.06	1.12	1.27	1.07
Taiwan	1.02	0.94	0.43	1.09	1.06	1.12	1.11	1.06
South Africa	0.95	0.91	0.34	1.06	1	1.07	1.11	1.06

Combined	L_{max5}_L_{inf}	L_{95}_L_{inf}	P_{mega}	L_{25}_L_{mat}	L_c_L_{mat}	L_{mean}_L_{opt}	L_{maxy}_L_{opt}	L_{mean}_L_{FeM}
Japan	0.81	0.73	0.04	0.75	0.69	0.81	0.9	0.99
Portugal	0.96	0.92	0.5	1.09	0.97	1.12	1.29	1.13
Taiwan	1	0.92	0.38	1.06	1	1.09	1.11	1.08
South Africa	0.94	0.89	0.28	1.06	1	1.05	1.06	1.04

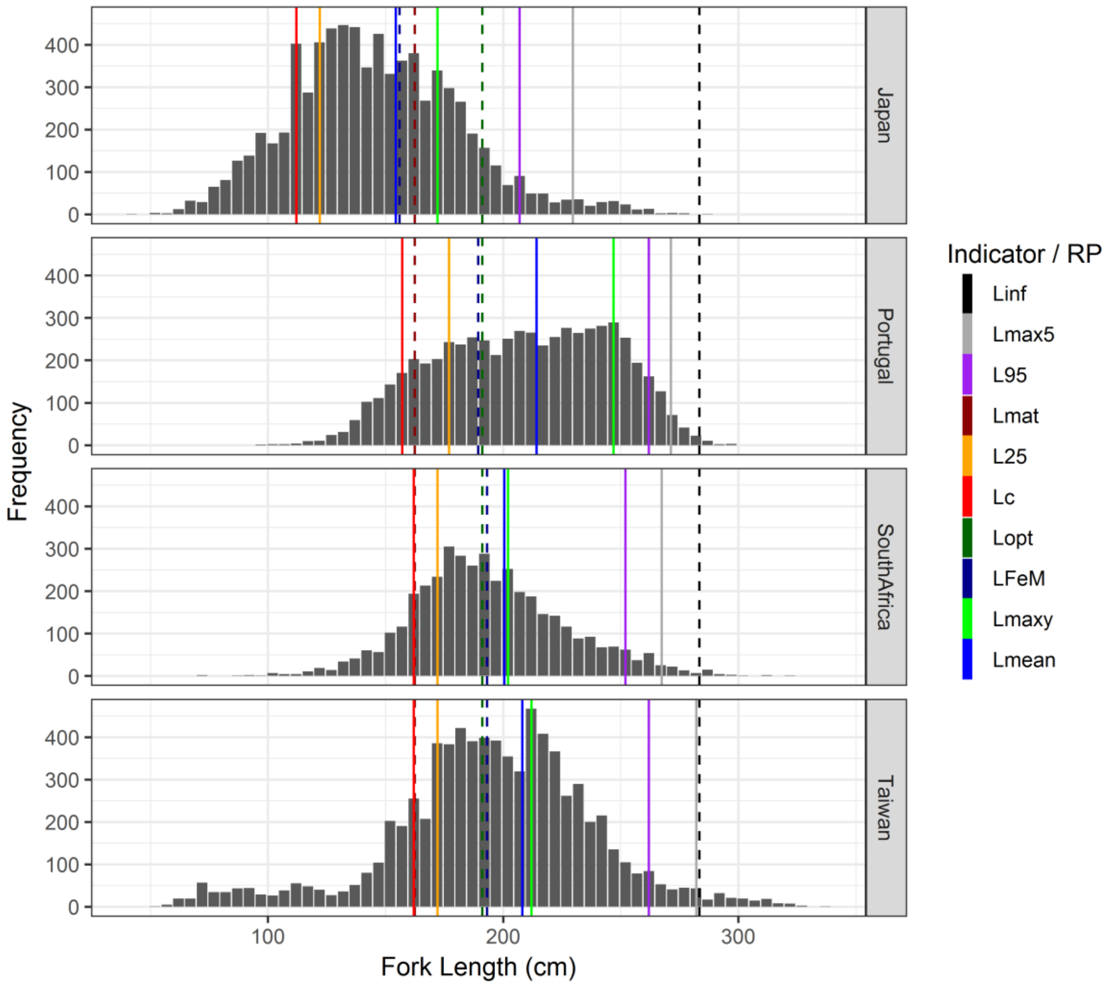

Figure 5. Length frequency of Indian Ocean blue shark (sexes combined) by nation with indicators (solid vertical line) and reference points (dashed vertical lines).

4. Discussion

Exploratory analyses provided inconsistent results across nations, indicating that issues of gear selectivity and/or differences in the spatial distribution of the fleets in relation to various components of the blue shark stock may influence LBI. Furthermore, there are potential issues of sample size (numbers of sharks measured, and number of trips), potential differences in the method of measurement (e.g. over the body or in line with the body) and type of measurement (e.g. total length or fork length).

The spatial population dynamics of sharks, which can include sex-based and size-based segregation may potentially affect underlying data and subsequent LBIs. Previous studies have examined the spatio-temporal distributions of juveniles and mature blue shark, and males and females in the region, showing that there are indeed both sex and size related regional segregation (Coelho et al., 2018). There may also have been subtle changes in the fishery (e.g. depth of lines, leader type, hook size/type, bait) which may influence size-based selection of blue shark, which should also be considered if possible.

Given the large size of elasmobranchs and the late age at maturity, the indicators based on conservation of immatures highlight that Lc and L25% often occur before fish mature. It is considered unlikely to have a mixed fishery that captures elasmobranchs to meet this indicator. Hence, this LBI may not be appropriate for management decisions.

The LBI analysed above cannot be used at the current time for management advice, as there would need to be further interpretation of the data in relation to the fishery and spatial population structure of the stock. The current reference points being used in ICES were derived for teleost fish and shellfish stocks, and so further studies to determine appropriate reference points for elasmobranchs are required. This should be a research priority in the future,

Whilst several nations are collecting length data for meaningful sample sizes, aggregating these data to the stock level may better provide an overall suite of LBIs. Appropriate raising factors (accounting for effort, removals (i.e. landings and dead bycatch) and spatial factors) could usefully be estimated.

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