Reproductive biology of the Blue shark (*Prionace glauca*) in the western Indian Ocean

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Abstract

This paper describes preliminary work to assess the sex-ratio and the length at 50% maturity of blue shark in the southwest Indian Ocean as part of the 'GERUNDIO' project . A total of 266 samples were collected and for 206 individuals the macroscopic maturity staging was reported as part of the project. The maturity staging was observed from sharks ranging in size from 53 to 275 cm straight fork length (SFL) for males and between 105 and 254 cm SFL for females and all sharks were caught in the southwest Indian Ocean off the coast of South Africa. According to available data, males individuals were much more numerous, especially in large individuals. Estimated size at 50% maturity was 201.7 cm SFL for males, 142.0 cm SFL for females and 190.5 cm SFL for both sexes combined. The maturity ogive estimated in our study is similar to the size at 50 % maturity used for blue shark stock assessment in the Indian Ocean, which uses a knife edge logistic maturity schedule with the length-at-50% maturity for females equal to 145cm.

Introduction

In 2020, an IOTC collaborative research project on was launched on the "Development and implementation of a sampling scheme to support the collection of biological samples and conduct analysis on these samples to provide improved estimates of age, growth and reproduction of tropical tunas, swordfish, and blue sharks for the Indian Ocean". The project is being led by AZTI (EU-Spain), with the participation of research institutions with experience in the IOTC area, and is funded by the European Union through FAO-IOTC. The aim of the project is to produce updated estimates of age, growth and reproduction parameters for the stock assessments of Indian Ocean tropical tunas (bigeye, skipjack and yellowfin), swordfish and blue shark.

The state of exploitation of the five species of interest for this project is evaluated using Stock Synthesis (Methot and Wetzel, 2013), a highly parameterized age-structured stock assessment software. Stock Synthesis explicitly describes the key fish dynamics and key processes of the population dynamic such as growth and reproduction, with equations that need accurate parameters from biological studies. The lack of knowledge on biological processes can reduce the reliability and confidence in stock assessment outcomes and undermine the sustainable management of fish stocks and fisheries. Therefore, age/growth and reproduction parameters are key to improve the stock assessment of those species. As such, the project plans to develop a sampling scheme to collect samples of otoliths, gonads and other body parts, and analyse them for

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age, growth and reproduction (in combination with samples collected in previous research initiatives) to produce updated estimates of key biological parameters using samples from the Indian Ocean for five important commercial species (three tropical tunas, swordfish and blue shark). Here, we present the results from the blue shark, *Prionace glauca* (BSH), reproductive sampling and work of the project.

The blue shark, *Prionace glauca* (Linnaeus, 1758) is one of the most abundant pelagic shark species with a circumglobal distribution found throughout tropical and temperate seas from latitudes of about 60°N to 50°S (Last and Stevens, 2009). It is mainly distributed up to depths about 350 m, however, deeper dives down to 1,000 m have been also recorded (Campana et al., 2011). The blue shark makes large-scale migrations (Queiroz et al., 2005; Campana et al., 2011), including complex horizontal and vertical movement patterns (Queiroz et al., 2016; Vandeperre et al., 2014). Size and sex differential distribution, with large fish dominating tropical waters and small fish occurring in temperate waters, have been observed (Coelho et al., 2018; Sippel et al. 2016; Joung et al. 2018).

Blue sharks in the Indian Ocean are mainly captured by tuna/swordfish longline, where it is the most important shark catch, and drift-net fisheries as target or by-catch species in the Indian Ocean. For example, in the swordfish longline fishery, in some areas and seasons, blue shark catches can account for more than 50% of the total catch and around 85–90% of the total elasmobranch catch (Coelho et al., 2012). In the Indian Ocean, the average annual blue shark landings reported to IOTC over the 2015–2019 period were 26,691 t (IOTC, 2021); however, total catch is estimated to be larger and around 55,000 tons.

The latest stock assessment for the Indian Ocean blue shark was carried out in 2017 and the IOTC determined that the stock was not overfished and was not subject to overfishing; however, the IOTC suggested catches should be reduced to increase the probability of maintaining spawning biomass above MSY reference levels (SB>SBMSY) over the next years. As for most pelagic shark species, there is still considerable uncertainty in the stock status results and, hence, management advice for blue shark in the Indian Ocean.

Blue shark reproductive studes are scarce and have generally been limited to the Pacific (Nakano, 1994; Joung et al., 2011; Zhu et al, 2011; Fujinami et al, 2017) and Atlantic Oceans (Castro and Mejuto, 2005; Montealegre-Quijano et al., 2014; Kouamé et al., 2019) where size at 50% maturity, size at maternity, fecundity and number of embryos, and size at birth were reported. A very old and a more recent blue shark reproduction study are available for the Indian Ocean(Gubanov and Grigoryev, 1975; Jolly et al., 2013; Zhu and Dai, 2014), the former providing size at maturity and number of embryos (Gubanov and Grigoryev, 1975). To improve the knowledge on blue shark reproduction and inform the stock assessment of this species, this paper presents preliminary results of blue shark sex-ratio and maturity in the southwest Indian Ocean.

Material & Methods

Blue shark samples were collected in 2018 (60 individuals) and 2021 (206 individuals) from commercial longline vessels operating in South Africa (**Figure 1**). The additional 60 individuals collected in 2018 were provided from the "Population Structure of Tuna, Billfish and Sharks in the Indian Ocean" project (PSTBS-IO; Davies et al. 2020). All sharks were sexed (except 19 sampled in 2018), determined from the presence or absence of claspers. Several length measurements (straight fork length, SFL; posterior length or Interdorsal Space, IDS - the projected straight distance between the most posterior insertion of the first dorsal fin to the most anterior insertion of the second dorsal fin; and clasper length, CL, in males) and total weight (TW) were recorded.

Figure 1. Map showing the location of blue shark samples in the South-Western Indian Ocean (Circles: 2021 samples, Crosses: 2018 samples).

The macroscopic maturity for males was determined based on claspers length and clasper calcification process. Left inner clasper length (from the tip of the clasper to the anterior margin of the cloaca) was measured and the degree of calcification of the clasper was recorded (uncalcified, partly calcified or fully calcified) following Fujinami et al. (2017) and FAO (2016). For example, in mature males, their claspers extend more than a third beyond the posterior edge of their pelvic fins (see table 1 for macroscopic maturity staging). For 2018 samples, macroscopic maturity staging was not determined.

Female blue shark macroscopic sexual maturation was classified in five stages following the description shown in **Table 1**. The size of the ovary, presence or absence and number of embryos, fertilized eggs, placenta, and an umbilical cord in the uterus was taken into account following the classification described by Fujinami et al. (2017). In immature females, the uterus is thin and white (juvenile stage) or slightly enlongated posteriorly (adolescent stage); the ovary is small and without mature follicles in both immature stages. In mature adult females, the uterus is enlarged but empty, and the ovary is enlarged with developing follicles. When adult females are at the pregnant stage, their uterus is enlarged with embryos or fertilised eggs present. Finally, when adult females are at the postpartum stage, their uterus is enlarged with no embryos or fertilised eggs present.

Table 1. Macroscopic maturation stages of male and female blue sharks from Fujinami et al. (2017).

Sex	Organ	Description	Maturity	Stage
MALE	Clasper, testis, and semen in the seminal vesicle	Claspers un-calcified, testis thin, and semen not present	Immature	**1**: Juvenile
		Claspers partially calcified, testis thickened, and semen may be present	Immature	**2**: Adolescent
		Claspers rigid and fully calcified, testis enlarged and predominant, and semen may be present	Mature	**3**: Adult
FEMALE	Uterus, ovary, and ovarian follicle	Uterus thin and white, and ovary very small	Immature	**1**: Juvenile
		Uterus thin and white but partly enlarged posteriorly, and ovary developing but no mature follicles	Immature	**2**: Adolescent
		Uterus enlarged but empty, and ovary enlarged with developed follicles	Mature	**3**: Adult
		Uterus enlarged with embryos or fertilised eggs present	Mature	**4**: Pregnant

		Uterus greatly enlarged, flaccid, and distended Placenta or umbilical cord may be present in uterus	Mature	**5**: Postpartum

The macroscopic maturation stage of each individual was converted into binary data (immature 0, mature 1) and the % of mature individuals by 5-cm SFL intervals, calculated as the ratio between number of mature individuals and the total number of individuals, was determined for males, females, and both sexes together for the statistical analysis. The size at 50% maturity (L_{50}) was estimated using a logistic regression model by fitting the proportion of mature individuals against the total length. This model is described as follows:

$$P = \frac{1}{[1 + e^{-(\alpha+\beta*SFL)}]}$$

Where P is the proportion of mature individuals in each 5-cm size interval, SFL is the SFL length of blue shark, and α, β are the coefficients of the logistic curve. The value of L_{50} is estimated from the negative ratio -α/β by substituting P = 0.5. A generalised linear model with a binomial error structure and logit-link function was used to estimate the α- and β-coefficients using R statistical software, version 4.0.4 (R Foundation for Statistical Computing, Vienna, Austria, see https://www.R-project.org/).

Results

Size distribution and sex-ratio of samples

A total of 266 individuals (made up of 168 males, 79 females, and 19 unsexed) were sampled (**Table 2**). The size ranged was 53 to 275 cm SFL for males (with an average of 195 cm ± 45) and 105 to 254 cm SFL for females (with an average of 191 cm ± 36) (**Figure 2a**). The size distribution of females and males covered similar sizes, however, males samples were much more numerous. The samples were skewed to males with a male:female sex-ratio of 2.1:1 (**Figure 2b)**.

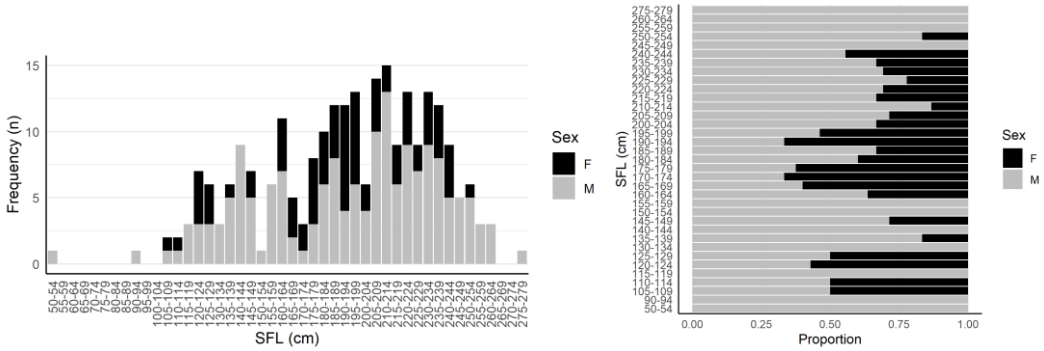

Figure 2. (a) Length-frequency distribution for female (black) and male (grey) blue sharks (*Prionace glauca*) caught in the southwest Indian Ocean. Length is Straight Fork Length (SFL) and (b) sex-ratio of sampled individuals by 5 cm SFL classes.

The relationships between SFL length and total weight (TW) is presented in **Figure 3**. However, in addition to the number of samples by sexes being too small, the weight was estimated by the observer which preclude to to obtain an accurate length-weight relationship.

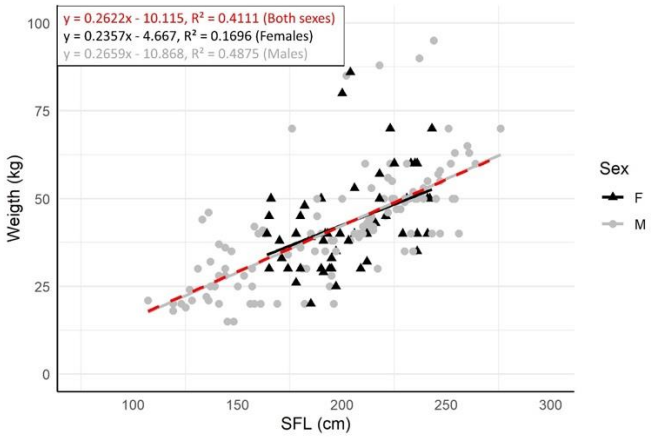

Figure 3. Body Length-weight relantionship in blue sharks (*Prionace glauca*) caught in the southwest Indian Ocean (n=175). Regression lines and equations are shown for females (black), males (grey) and both sexes combined (red). Body length is Straight Fork Length (SFL).

Size at sexual maturity

Males classified macroscopically as immature (stage 1, N= 27) varied in size from 107 to 260 cm SFL showing uncalcified claspers between 6 and 23 cm CL (mean ± SD; 13 ± 4) (**Table 2**). Adolescent maturing males (stage 2, N = 52) ranged between 107 and 260 cm SFL, and their claspers were partially calcified claspers and ranged from 10 to 30 cm (mean ± SD; 21 ± 5). And 62 males ranging from 148 to 276 cm SFL were macroscopically classified as matures, with claspers fully calcified and measuring 11–31 cm (mean ± SD; 24 ± 4). The claspers develop and calcify linearly with blue shark size (**Figure 4**).

Table 2. Average values and ranges for Straight Fork Length (SFL), Weight, Interdorsal Space length (IDS) and Clasper Length (CL) for each reproductive stage in male and female blue shark (*Prionace glauca*) caught in the southwest Indian Ocean.

Sex	Stage	N	SFL (cm)		Weight (kg)		IDS (cm)		CL (cm)	
			Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Males	1	27	150±35	107-260	29±8	18-46	38±8	29-66	13±4	6-23
	2	52	202±33	137-263	40±11	15-70	52±8	34-67	21±5	10-30
	3	62	223±27	148-276	48±17	15-95	56±8	37-70	24±4	11-31
Females	1	-	-	-	-	-	-	-	-	-
	2	14	191±27	146-254	40±7	30-48	45±6	29-51	-	-
	3	6	183±32	140-229	45±5	40-60	51±7	43-61	-	-
	4	37	208±22	165-243	43±16	20-86	53±5	43-64	-	-
	5	8	212±23	178-241	44±9	32-60	57±8	51-65	-	-

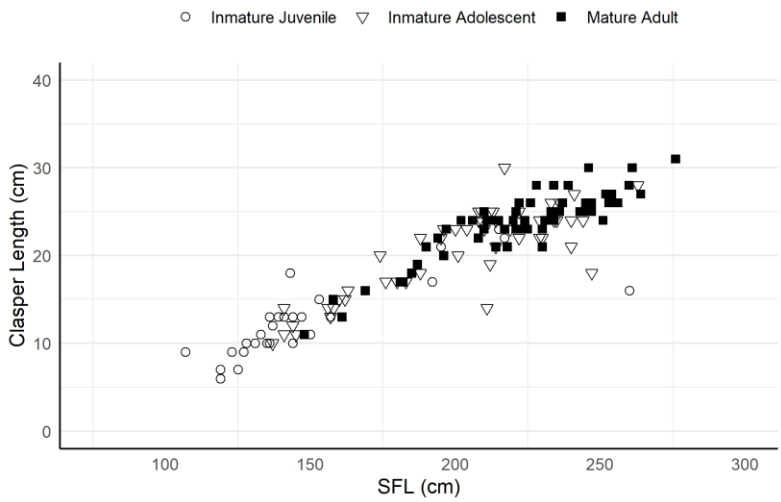

Figure 4. Clasper-body length relantionship compared with calcification degree in males of blue shark (*Prionace glauca*) caught in the southwest Indian Ocean (n=140). Body length is Straight Fork Length (SFL).

Fourteen females, from 146–254 cm SFL, were classified macroscopically as maturing adolescent females (stage 2) and had ovary developing but no mature follicles (**Table 2**). Fifty one females were classified macroscopically (stage 3 to 5) as mature females: 6 were classified as mature with enlarged uterus and ovary with developed follicles ranging from 140 to 229 cm SFL, 37 pregnant females with enlarged uterus with embryos or fertilised eggs with a size range of 165-243 cm SFL, and 8 were classified postpartum raging from 178 to 241 cm TL, with the uterus greatly enlarged, flaccid, and the possible presence of distended placenta or umbilical cord.

Estimated size at 50% maturity was 201.7 cm SFL for males, 142.0 cm SFL for females and 190.5 cm SFL for both sexes combined (**Figure 5**).

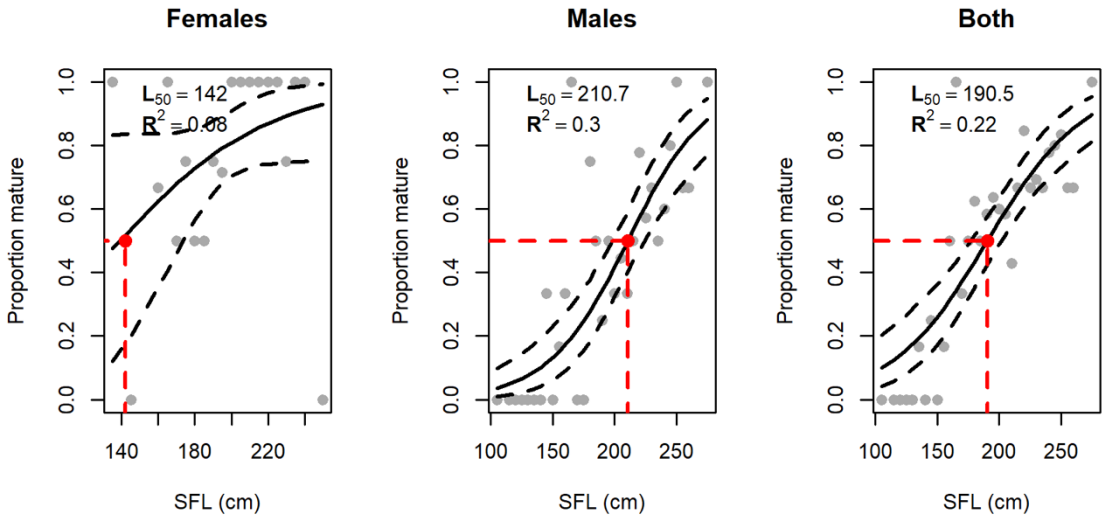

Figure 5. Length at maturity ogives for female, male and both sex combined blue shark (*Prionace glauca*) caught in the southwest Indian Ocean. Size class interval is 5 cm of Straigth Fork Length (SFL).

Unfortunately, the litter size was not recorded consistently by counting the number of embryos during all trips, and thus, it was not possible to conduct proper fecundity estimations. However, observers onboard reported more than 10 embrios per pregnant females, and an average of 20-25 or more embryos per pregnant female.

Discussion

All the individuals sampled in the present study were smaller than 280 cm SFL, which is smaller than individuals collected in other studies both in the Indian Ocean and other oceans. This could be due to the different spatial distribution of blue shark by size as shown by Coehlo et al. (2017), who reported that larger blue sharks generally occurr in equatorial and tropical regions whereas smaller individuals generally occur in higher latitude temperate waters. They also found that nursery areas in the Indian Ocean occur in temperate waters, particularly in the southwest and southeast Indian Ocean off South Africa and Australia, respectively. The different spatial distribution by size for blue shark could also lead to variability in observed maturity by size, which may have contributed to the relatively low L_{50} estimate in the current study. However, the limited sampling for females was also a likely contributing factor. Thus, additional observations of macroscopic maturity stages of blue shark in the western and other areas of the Indian Ocean is needed to provide further insight into the maturity schedule of blue shark in the Indian Ocean.

The individuals sampled in the present study consisted mainly of mature individuals (80 % of the individuals from which macroscopic maturity staging was available) of both sexes with males more numerous and slightly larger than females. Although our estimation of maturity ogive may be limited due to the low number of samples (particularly for females) and limited geographic range of samples, our estimation of size at 50% maturity for females (142 cm SFL) is smaller than those reported by other studies in the Pacific, Atlantic and Indian Ocean; which ranged from 152 to 185 cm SFL (Nakano 1994; Carrera-Fernández et al., 2010; Joung et al., 2011; Fujinami et al., 2017; Francis and Duffy, 2005; Pratt, 1979, Jolly et al., 2013; Montealegre-Quijano et al., 2014; Gubanov and Grigoryev, 1975). However, the size at 50% maturity for females estimated in our study is similar to the size at 50% maturity used for blue shark stock assessment in the Indian Ocean, which uses a length-based knife edge logistic maturity schedule with the length-at-50% maturity for females equal to 145cm (Nakano and Seki 2003).

The size at 50% maturity for males estimated in the present study (210.7 cm SFL) is, in general, slightly larger than those reported in other studies in the Pacific and Atlantic Oceans; which ranged from 142 to 183 cm SFL (Nakano 1994; Carrera-Fernández et al., 2010; Joung et al., 2011; Fujinami et al., 2017; Francis and Duffy, 2005; Pratt, 1979, Jolly et al., 2013; Montealegre-Quijano et al., 2014). This might be due to the spatial variability of blue shark by size with smaller late maturing individuals distributed in the temperate waters of the southwest Indian Ocean.

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