Billfish size-at-maturity in the western Indian Ocean

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Abstract

Billfish are caught as bycatch in tropical fisheries. Most billfish species stocks are evaluated by RFMOs and stock assessment models generally require reproductive biology parameters such as the size-at-maturity. However, the reproductive biology of billfish species in the Indian Ocean is poorly known. The objective of this study is to fit maturity curves by sex for billfish species such as the black marlin, the blue marlin, the striped marlin, the shortbill spearfish, the Indo-Pacific sailfish, and the swordfish, and to determine the L50 (size at which 50% of the individuals are mature). We used 1480 samples from scientific cruises carried out by YugNIRO (1969-1989) and IRD (2003-2015) in the Indian Ocean to test and compare two methods for fitting maturity curves. The method that is commonly used consists in building the maturity curve from proportions of mature individuals by size class intervals with a logistic curve. The alternative method that we propose here is a Binomial regression that directly fits a logistic curve from binary immature/mature data. We showed that the Binomial regression method is the better method. We were able to fit maturity curves and determine L50, including a confidence interval, for most species by sex. For the black marlin, the L50 is 185 cm (LJFL) for males and none could be found for females. The L50 for striped marlins is 232 cm for females and could be determined for males. The sailfish reaches maturity at 203 and 210 cm for females and males respectively. Finally, swordfish females and males have a L50 of 152 and 129 cm.

Keywords

Billfish | Size-at-maturity | Binomial regression | Indian Ocean | Bycatch |Tropical fisheries

1. Introduction

Tropical fisheries in the Indian Ocean (e.g. drifting gillnet, pelagic longline, purse seine) mostly target tuna species such as the yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*), skipjack tuna (*Katsuwonus pelamis*) and albacore tuna (*Thunnus alalunga*), but billfish species, that are non-targeted, are regularly caught: the black marlin (*Makaira indica*; BLM), blue marlin (*Makaira mazara*; BUM), striped marlin (*Tetrapturus audax*; MLS), sailfish (*Istiophorus platypterus*; SFA), and shortbill spearfish *(Tetrapturus angustirostris*; SSP) (Chevallier et al., 2015; Sabarros et al., 2016; IOTC, 2018). These billfish are part of the bycatch and can be retained or discarded

In the frame of the ecosystem approach to fisheries, stock abundance levels and status of bycatch species such as the billfish are now assessed by tuna-RFMOs, notably in the Indian Ocean by the IOTC. Stock assessment models sometimes require data on the biology of species such as their natural mortality, recruitment of juveniles to the spawning stock, growth, reproduction, migration patterns, etc. (Sparre and Venema, 1996). However, little is known on the reproductive biology of billfish species (Pons et al., 2016), specifically in the Indian Ocean, and notably the size-at-maturity.

The objective of the present study is to provide new information on the reproductive biology of billfish species in the Indian Ocean, in particular the size-at-maturity (L50, size at which 50% of the individuals are mature) that will be deducted from maturity curves. Here we used data collected during scientific cruises carried out by YugNIRO (URSS) and IRD (France) to build maturity curves by sex using generalized linear models and extract the L50 for each billfish species.

2. Material and methods

2.1. Data description

Data used in this study were collected in the western Indian Ocean by YugNIRO (Southern Scientific Research Institute of Marine Fisheries and Oceanography, URSS) and IRD (Institut de Recherche pour le Développement, France). YugNIRO carried out longline and purse seine scientific surveys between 1969 and 1989 (Romanov et al., 2006). IRD data concern longline scientific surveys carried out between 2004 and 2015 that were part of various research projects such as ECOTEM (2004), SWIOFP (2008-2010), and PROSPER 1 and 2 (2010-2015) (Cauquil et al., 2015).

During these scientific cruises, scientists collected data on the billfish individuals that were caught including the species, length of individuals (lower-jaw fork length, LJFL, in cm), and sex and maturity stage (Table 1; stages: I, II, II, IV, V, VI; Sakun and Butskaya, 1968) through the examination of gonads.

Data are available for five Istiophoridae species: the black marlin, blue marlin, striped marlin, sailfish and shortbill spearfish, and one Xiphiidae species: the swordfish.

2.2. Data analysis

2.2.1. Data preparation

In order to build maturity curves for each billfish species, information on the size, sex and maturity stage are necessary.

Individual sizes were not always collected as LJFL. When this was the case, e.g., eye-fork length (EFL) or other measure types, we used length-length relationships to convert the length into a LJFL (see details in Girault, 2019).

Uncertain maturity stages noted II-III or III-IV or IV-V were sometimes encountered in the databases. We used the gonado-somatic index (GSI; Valdés et al., 2004) to reclassify uncertain maturity stages to the more appropriate one (see details in Girault, 2019).

Also, after data exploration, we decided to filter out potential outliers by keeping the two-sided 95% quantile for each maturity stage by sex and species.

Final data counting 1480 samples are presented in Figure 1.

2.2.2. Fitting a maturity curve

Raw data with maturity stages were binarized into two classes corresponding to immature (coded 0) and mature individuals (coded 1). Immature individuals belong to maturity stages I and II, while mature individuals belong to stages III, IV, V and VI.

In this study, we tested two methods for building maturity curves: the first one that we call the “Proportion method” is the classic and commonly used method, and the second one called hereafter “Binomial method” is the alternative method we propose here.

Proportion method. This method consists in calculating the proportion of mature individuals by size class intervals to which will be adjusted a logistic function. This is the most common method used to build maturity curves for fish (e.g., Trippel and Harvey, 1991; Chen and Paloheimo, 1994; Chiang et al., 2006; Poisson and Fauvel, 2009; Sun et al., 2009; Kopf et al., 2012; Zhou et al., 2018).

The size class interval being a critical point in this method, we tested a range of size class intervals: 1, 2, 5, 10 and 40 cm.

Binomial method. The Binomial method consists in modeling the probability of realization of the binary response Y, here “mature” (1) and “immature” (0), as a function of X, here the size of individuals, using a Binomial logistic regression (Zuur et al., 2007). Despite being a very classic statistical method, it was never used to build maturity curves for fish to our knowledge.

For both methods we controlled the quality of the fitted models by considering the distribution of residuals, QQ plots, and residuals versus fitted values.

2.2.3. Size-at-maturity (L_{50})

The size at which 50% of the individuals are mature (L50) can be identified graphically (e.g., Figure 2) but also calculated using the regression parameters *a* and *b* from the fitted maturity curves, with *Y* = 0.5 following the equation:

$$L50 = (log(Y/(1-Y)-a)/b$$

For the L50 we also provide a 95% confidence interval.

3. Results

3.1. Comparison of the two methods

Using the example of female striped marlins, we compared the "Proportion method" and the "Binomial method". Specifically, we assessed the performance of the two models by comparing the estimated L50 and confidence interval (Figures 2 and 3). We found that whichever the method used (and for the "Proportion method" between the size class intervals considered) the estimated L50 was comparable. The confidence interval of the L50 however increases with the size class interval in the "Proportion method", the tighter confidence interval being for the smaller size class (1 cm). In comparison, the confidence interval obtained with the "Binomial method" is tighter than the ones obtained with the "Proportion method".

3.2. Size-at-maturity

The L50 (and confidence interval) presented here were obtained using the "Binomial method".

Black marlin. The maturity curve for male black marlins based on 35 individuals is significant (Table 2) and suggests a L50 of 185 cm [154-212] (Table 3; Figure 4A). None could be obtained for females (Table 2).

Blue marlin. We could not either fit maturity curves using blue marlin data (Table 2).

Striped marlin. A maturity curve could be fitted for females striped marlins using 151 individuals (Table 2) that suggests a L50 of 232 cm [224-244] (Table 3; Figure 4B). For males, the regression was not significant (Table 2).

Sailfish. Maturity curves were obtained for both sexes (Table 2). Using 515 individuals we estimated a L50 of 210 cm [199-234] for male sailfish (Table 3; Figure 4C). For females, the maturity curve built from 588 individuals suggests a L50 of 203 cm [194-215] (Table 3; Figure 4D).

Shortbill spearfish. The small sample size did not allow to fit maturity curves for the shortbill spearfish (Table 2).

Swordfish. Maturity curves could be fitted for both sexes (Table 2). The L50 of male swordfish is 129 cm [110-141] with 45 individuals considered (Table 3; Figure 4E), while it is 162 cm [150-179] for females with 51 individuals considered (Table 3; Figure 4F).

4. Discussion

Only a few studies have provided so far information on the reproductive biology of billfish species in the Indian Ocean (e.g. Poisson and Fauvel, 2009; Zhou et al., 2018). Using data collected by YugNIRO and IRD over decades in the Indian Ocean, we were able to determine maturity curves and propose estimations of the size-at-maturity by sex, including a confidence interval, for 4 billfish species: the black marlin, striped marlin, sailfish and swordfish.

For the black marlin, we found that males reach their size-at-maturity at 185 cm which is superior to the 167 cm proposed by Zhou et al. (2018), which remains however within the confidence interval [154-211] we determined. Nonetheless, Zhou et al. (2018) results are questionable since males and females were pooled together. Using our data, we were not able to fit a maturity curve for female black marlins.

Our data suggest that striped marlins reach maturity at 232 cm for females and it is again superior to the 177 cm from the study of Zhou et al. (2018) where males and females were not discriminated. Moreover, this latter value is out of the range of the confidence interval [224-244] that we determined for females. It is also the case for results from the Pacific Ocean where females reach the sexual maturity at 210 cm (Kopf et al., 2012). The difference with our results might be explained by the geographic origin of the samples collected.

In our study, the size-at-maturity for female sailfish is 203 cm [194-215] and 210 cm [199-234] for males. It is however uncommon to observe that males are mature at a greater size than females (Weatherley and Gill, 1987; Stamps, 1993). Chiang et al. (2006) found in the Pacific Ocean that females reach maturity at 166 cm, and Zhou et al. (2018) suggested 192.6 cm in the Indian Ocean (for females and males pooled together). For both studies, values are inferior to that we found and none are in the confidence interval [194-215] determined for females. Despite the concerns with the fact that males and female samples were pooled together in Zhou et al. (2018), the value proposed in this study is closer to our result than the L50 suggested by Chiang et al. (2006), the latter corresponding to samples collected in another ocean.

For the swordfish, we determined that females and males respectively reach maturity at 162 and 129 cm. In a study conducted by Poisson and Fauvel (2009) in the Indian Ocean, the authors suggested 170 cm for females and 120 cm for males, which fits within the confidence intervals we determined, respectively [150-179] for females and [110-141] for males. Both results are comparable. Also, in this case, we respect the general trend in fish populations where females become mature at a greater size than males (Weatherley and Gill, 1987; Stamps, 1993).

No maturity curves could be fitted for the blue marlin despite the consequent amount of data available. This might be explained by the fact that maturity stages may not have been properly identified, indeed we can see in Figure 1 female blue marlins in stage II (immature) that are very large (>250 cm). Also, there can be some species misidentification which is rather common between marlin species (black/blue/striped) (Chevallier et al., 2015). For the shortbill spearfish also we could not fit maturity curves and this might be due to the relatively small sample size compared to the other species.

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6. Tables

Table 1. Macroscopic description of maturity stages as described by Sakun and Butskaya (1968).

Maturity stage		External description for females	External description for males
I	Juveniles	Gonads looks like thin cord of white-pink colour attached to abdominal cavity. Sex determination is extremely difficult without microscopic examination.	Gonads looks like thin cord of white-pink colour attached to abdominal cavity. Sex determination is extremely difficult without microscopic examination.
II	Immature	Ovaries increase in size and weight, have dense cover of light-pink or lemon colour, are characterized by the presence of egg-bearing plates of up to 1 mm. in height, blood vessels are poorly developed.	Testes are thin, grey, heterogeneous in colour at trans-sections. Gonads are nearly triangular at sections.
III	Early maturation	Ovaries occupy a considerable part of abdominal cavity, they are of light-yellow colour, and eggs are pink-orange. The eggs are seen clearly with the unaided eye, their diameter does not exceed 625 microns at longitudal section of ovary, a cavity and well-formed egg-bearing plates with the height of 1 cm are noted inside.	Testes occupy considerable part of abdominal cavity and are of pale-milky colour. At trans-section the edges do not gutter.
IV	Mature pre-spawners	The cover of ovaries is thick as before, a well-formed cavity is noted inside at longitudal section. The diameter of the biggest eggs is 800 microns (Fig. 2d). The eggs are of yellow colour, well seen with the unaided eye, some of them become transparent by the end of the stage.	Testes of pale-pink colour occupy half of abdominal cavity, the edges gutter at trans-section.
V	Spawners, ripe fish	Eggs often leaking from alive or dead whole fish. The ovaries occupy about 3/4 of abdominal	Spermatophores often leaking from alive or dead whole fish. Testes are white,

		cavity volume. Their cover is as thick as before. Egg-bearing plates are very high, eggs are 700-800 microns in size. The diameter of the biggest eggs reaches the maximal size of 100 microns, they are transparent and easily drop out of their nests.	the edges gutter swiftly at section.
VI-IV and VI-III	Post-spawners, intermediate period of spawning for multiple-batch spawning fish	This stage is noted for individuals that had spawned some part of their sex products. Ovaries are yellow with reddish. Eggs similar with stage IV or III is visible.	Male gonads at this stage are flabby, reddish.
VI-II	Post-spawners, spent	Ovaries are stretched and have a big cavity. The cavity inside the ovary is red, inflamed sex glands are bluish-pink. This stage characterizes post-spawning state of ovaries.	

Table 2. Summary statistics of maturity curve fits using the "Binomial method" for the black marlin (BLM), blue marlin (BUM), striped marlin (MLS), sailfish (SFA), shortbill spearfish (SSP), and swordfish (SWO). Significance of tests: 99% (**), 95 (*), not significant (-).

Species	Sex	N	*a*	P-value	*b*	P-value
BLM	M	35	-6.34	*	0.034	*
	F	45	-	-	-	-
BUM	M	126	-	-	-	-
	F	129	-	-	-	-
MLS	M	85	-	-	-	-
	F	151	-11.3	**	0.05	**
SFA	M	515	-3.8	**	0.018	**
	F	588	-3.74	**	0.018	**
SSP	M	16	-	-	-	-
	F	21	-	-	-	-
SWO	M	45	-6.9	**	0.054	**
	F	51	-11.33	**	0.07	**

Table 3. Estimated size-at-maturity (L50) for the billfish species: black marlin (BLM), blue marlin (BUM), striped marlin (MLS), sailfish (SFA), shortbill spearfish (SSP), and swordfish (SWO). The confidence interval (CI) of the L50 is given in brackets.

Species	Sex	N	Sample range (cm)	L50 (cm)	L50 CI (cm)
BLM	M	35	141 ≤ LJFL ≤ 280	185	[154-212]
	F	45	129 ≤ LJFL ≤ 306	-	-
BUM	M	126	122 ≤ LJFL ≤ 265	-	-
	F	129	168 ≤ LJFL ≤ 282	-	-
MLS	M	85	146 ≤ LJFL ≤ 240	-	-
	F	151	147 ≤ LJFL ≤ 277	232	[224-244]
SFA	M	515	135 ≤ LJFL ≤ 237	210	[199-234]
	F	588	137 ≤ LJFL ≤ 270	203	[194-215]
SSP	M	16	138 ≤ LJFL ≤ 174	-	-
	F	21	126 ≤ LJFL ≤ 177	-	-
SWO	M	45	107 ≤ LJFL ≤ 190	129	[110-141]
	F	51	85 ≤ LJFL ≤ 215	162	[150-179]

7. Figures

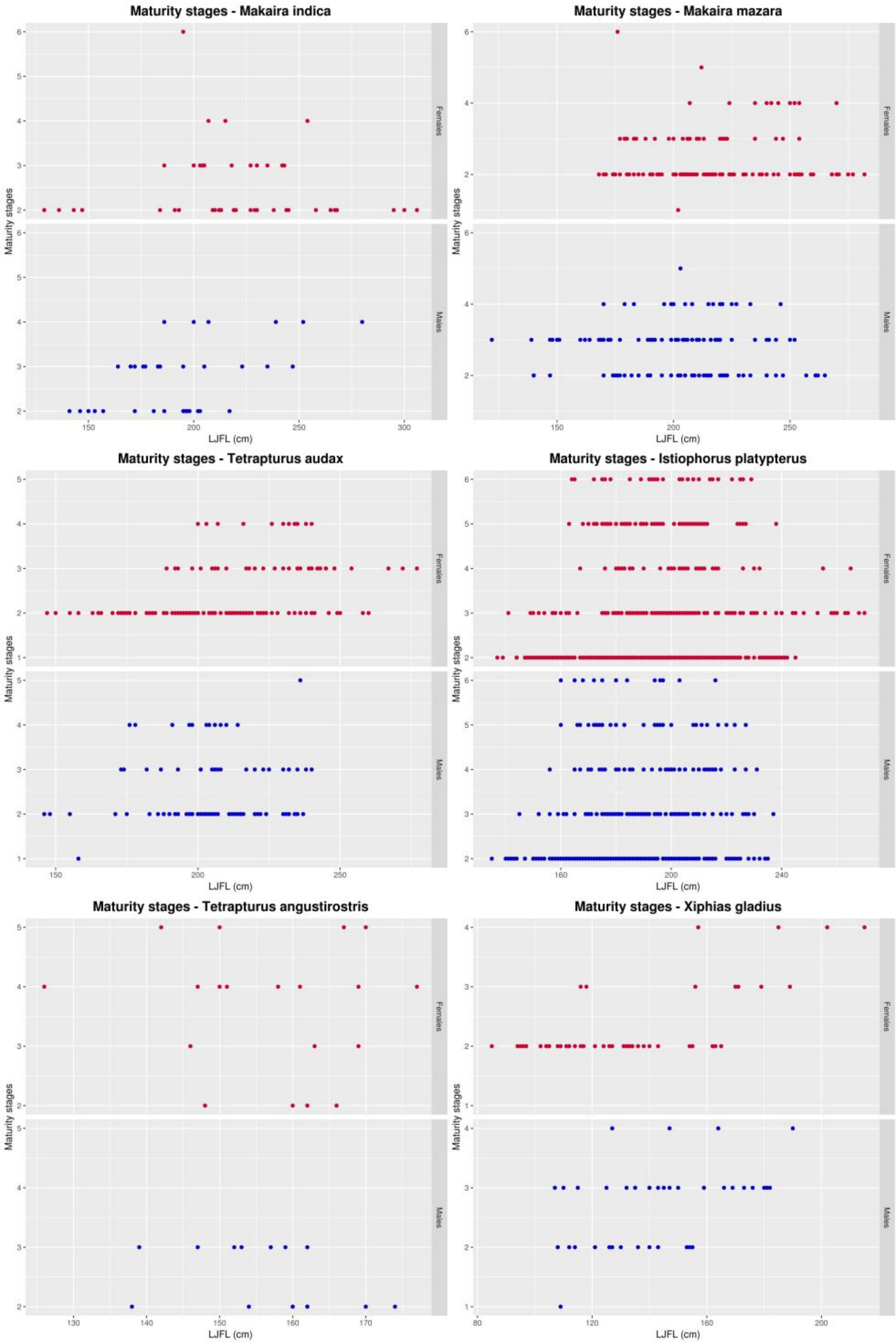

Figure 1. Length of individuals (LJFL in cm) according to the maturity stage for the black marlin (M. indica), blue marlin (M. nigricans), striped marlin (T. audax), sailfish (I. platypterus), shortbill spearfish (T. angustirostris), and swordfish (X. gladius).

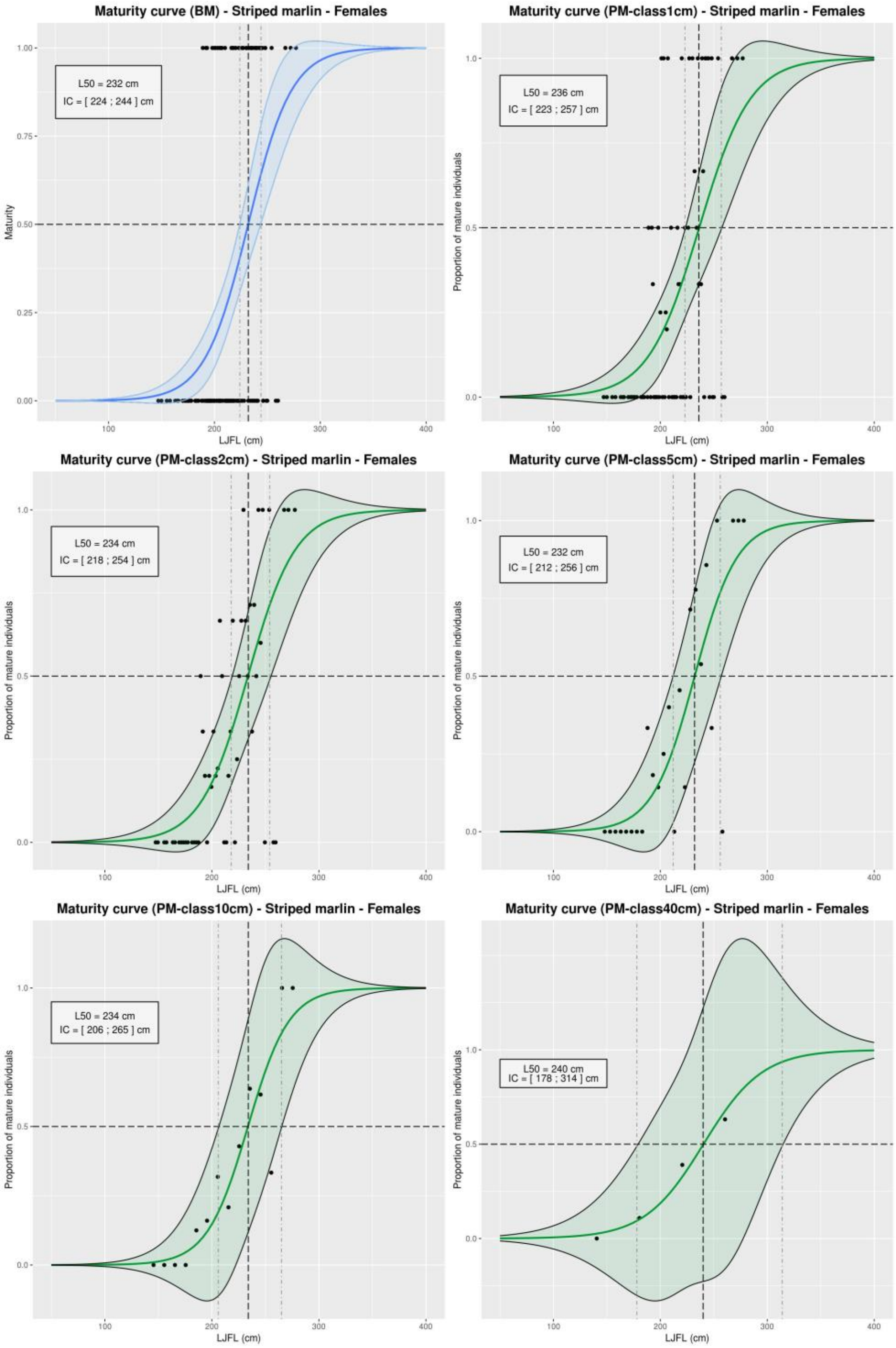

Figure 2. Comparison of maturity curves for female striped marlin (MLS) obtained with the binomial method (blue) and the proportion method (green; with 1, 2, 5, 10, 40 cm size class interval).

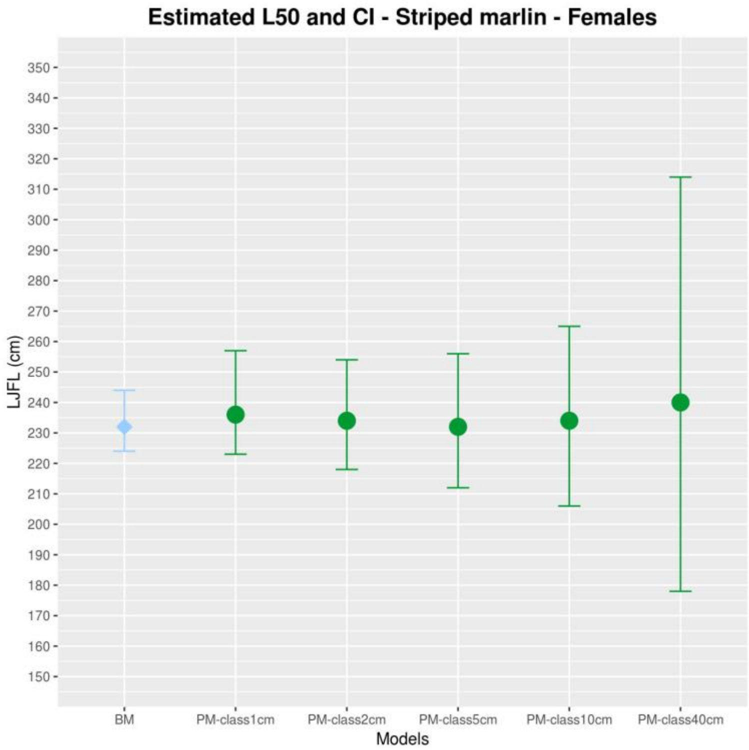

Figure 3. Estimated L50 and confidence intervals for female striped marlins (MLS) obtained with the binomial method (blue) and the proportion method (green; with 1, 2, 5, 10, 40 cm size class interval).

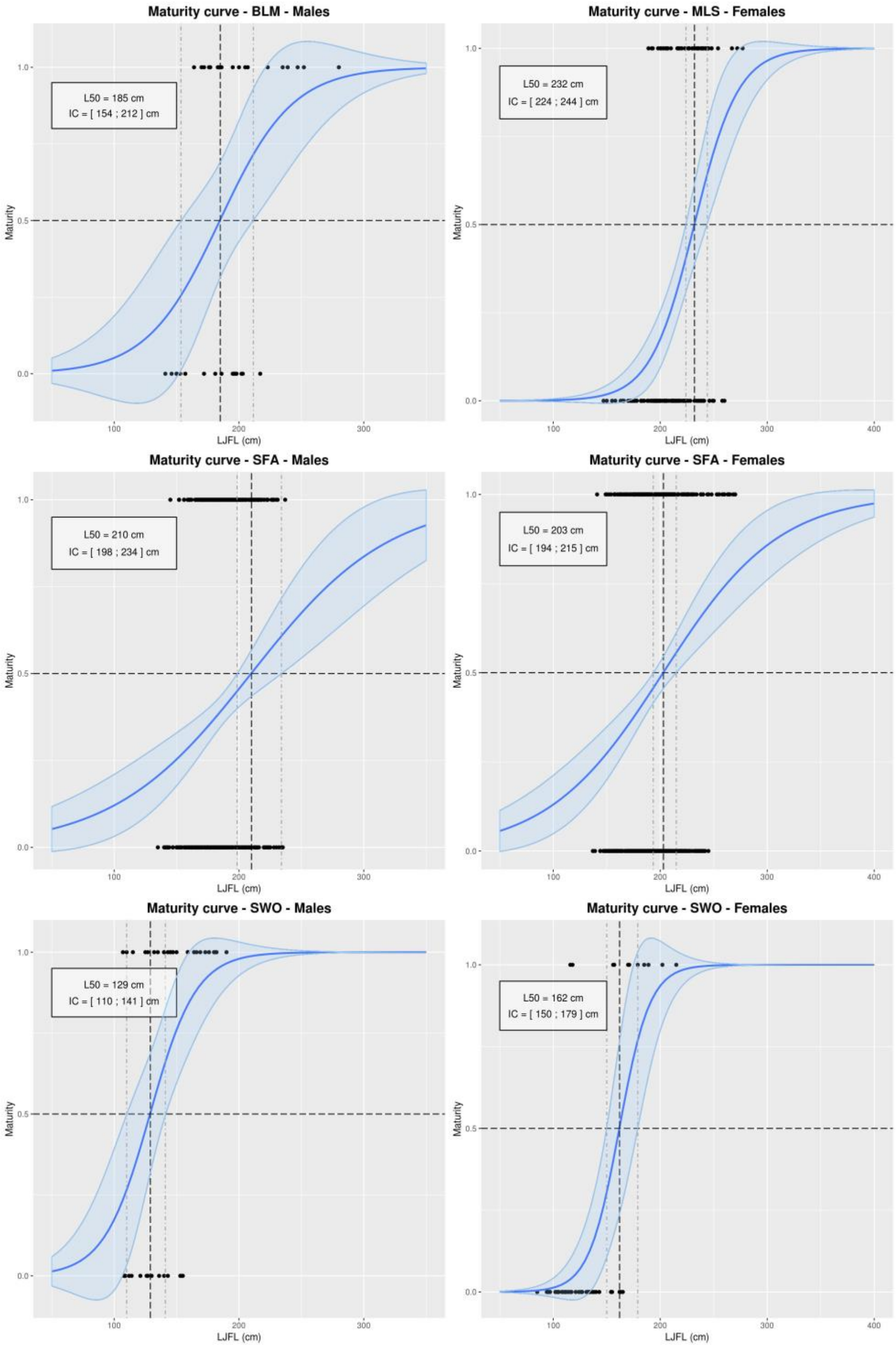

Figure 4. Maturity curves, L50 and its confidence interval obtained with the "Binomial method" for the black marlin (BLM) for males only, striped marlin (MLS) for females only, sailfish (SFA) for both sexes, and swordfish (SWO) for both sexes. On the left and right columns, males (M) and females (F) respectively. Black dots represent the binary mature/immature data.