Stock Assessment of kingclip (*Genypterus blacodes*) in the Falkland Islands using length-based methods and yield per recruit approach

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Summary

The kingclip is a benthic demersal species distributed throughout the southern hemisphere. Its low resilience (slow growth, late maturation) makes it vulnerable to exploitation. It is also a top predator that feeds on other benthic and demersal species. The decline of a top predator could lead to cascade effects, affecting an entire community. However, in the case of the kingclip, the effects of its decline on the community are currently unknown. In this report, two length-based approaches were used to assess the stock status of the kingclip in Falkland Islands waters (LB-SPR and LBB). A yield per recruit analysis was also performed to explore the impact of different catch lengths on the population dynamics of the cohort. Both length-based approaches confirm that the kingclip is being caught at too small sizes by the commercial fishery and the stock is currently below the assumed limit reference points (0.5 B_{MSY} proxy for the LBB, and 0.2 SPR for LBSPR models). The yield per recruit method also showed that fish are being caught at too small sizes and that catching larger fish would be necessary to optimise the YPR. A length at 50% selectivity closer to 80 cm would give a better theoretical yield per recruit while maintaining 40% spawning biomass per recruit. The results from a recent stock assessment of the kingclip in Falkland Islands waters showed contradictory results, with the biomass being estimated below or above the reference points (50% of the unfished total biomass) depending on the relative abundance index employed in the model. However, the results from both length-based models from this report are in concordance with the stock assessment done for the whole kingclip stock by the Argentine government, which showed biomass levels below the limit reference point (20% of the unfished spawning biomass). Given the results (stock close or below the assumed limit reference points) management actions may be needed to recover the health of the stock.

Introduction

Given the social and economic importance of fisheries, their conservation and management are vital for the continuity of the activity. However, for a good management strategy, quality data input is essential (Davies *et al.*, 2023). On the other hand, fisheries information is not always reliable, and its amount is generally limited (Bradley *et al.*, 2019). Some methodologies have been developed to assess the stock status when data is limited. One source of information is the size-structure of the catch. When length information is available, some length-based methods have been developed (Hordyk *et al.*, 2015a; Froese *et al.*, 2018).

In the Falkland Islands Fisheries Department (FIFD), information on the catch size-structure is available since 1988. Length information is directly measured by the fishery observers. Thus, fish length information that is measured directly on-board is considered more reliable than total catch weight that is reported from weight estimations from the vessel crew. However, it is realistically impossible to have an observer present on all vessels at all times (Bradley *et al.*, 2019), and therefore the length-based information becomes limited in the form of samples. On the other hand, the FIFD has conducted fishing surveys regularly since 2010, where the information is collected following a scientifically designed protocol.

Other information has also been collected by the FIFD since 1988, such as fishing effort. Given this information, it is possible to calculate a standardized catch per unit effort (CPUE) and apply assessments based on catch and CPUE time-series (surplus production, ASPM). However, for the kingclip (*Genypterus blacodes*), the standardized CPUE for different fisheries in Falkland Islands waters was considered unreliable, with different datasets leading to contradictory results in the assessments (García, 2024). Therefore, this report aims to evaluate the kingclip stock status from a different perspective, using length-based approaches.

The kingclip is a benthic demersal species distributed throughout the southern hemisphere. Its low resilience (slow growth, late maturation; Froese & Pauly, 2024) makes it vulnerable to exploitation. Kingklip tend to concentrate in some areas on feeding grounds (Ivanovic, 1990; Di Marco, 2022), which are mostly associated with rocky bottoms off the continental slope (Brickle *et al.*, 2003) and between 100 m to 200 m depth (Sammarone, 2023). It is also a top predator that feeds on other benthic and demersal species (Bellegia *et al.*, 2023). The decline of a top predator could lead to cascade effects, affecting an entire community. Those cascade effects are widely documented since the publication of the ground-breaking work of Paine (1980). The decline of large predators is expected to influence smaller-bodied mesoconsumers and their pray (Heitaus *et al.*, 2008). In the case of the kingclip, the effects of its potential decline on the community are currently unknown.

Two length-based approaches were used to assess the stock status of the kingclip in Falkland Islands waters: the length-based spawning potential ratio (LB-SPR) method (Hordyk *et al.*, 2015a) and the length-based Bayesian biomass (LBB) method (Froese *et al.*, 2018). These methods can provide a complementary assessment of the *G. blacodes* stock status in

Falkland Islands waters, offering a set of tools to inform the fishery management decisions. The results of this assessment will help estimate sustainable harvesting levels and inform management recommendations to ensure long-term resource availability and protect marine biodiversity in the region.

A yield per recruit (YPR) analysis was also performed (Beverton & Holt, 1957). YPR is commonly used to test alternative management strategies when historical information about recruitment in the studied population is limited. From there it is possible to obtain biological reference points. Per recruit analyses involve tracking a cohort throughout its lifetime. In this type of analysis, the absolute size of the cohort is not important, but rather relative changes in abundance and catch (or yield) over time. This type of analysis allows to measure the impact of different harvest strategies (selectivity patterns and exploitation rates) on the population dynamics of the cohort. For this method, harvest strategies refer specifically to selectivity patterns and exploitation rates.

Methods

For the assessment, two different length-based approaches were evaluated. The Length-based Bayesian Biomass (LBB, Froese *et al.*, 2018), and the Length Based Spawning Potential Ratio (LB-SPR, Hordyk *et al.*, 2015a). These approaches rely on length frequency data, species life-history parameters, and selectivity of the fishery. LBB requires less life-history input parameters to run. Moreover, an assessment can be carried on with no added input parameters, as the model includes its own default priors. However, for more precision for the assessed stock, local parameters are recommended (Froese *et al.*, 2018).

The required input parameters were obtained from local literature (Ramos & Winter, 2022) and from the R package *FishLife* (Thorson *et al.*, 2023) at the species level. All the assessments were performed with R (R Core Team, 2022) in R Studio (Posit team, 2023).

LBB

This method analyses the size composition data from catches, where all parameters are estimated simultaneously with a Bayesian Monte Carlo Markov Chain (MCMC) approach. Growth in body length is assumed to follow the von Bertalanffy (VB) growth equation, in the form given by Beverton and Holt (1957):

$$L_t = L_{inf}[1 - e^{-k(t-t_0)}]$$

Where L_t is the length at age t, L_{inf} is the VB asymptotic length, k is the rate by which L_{inf} is approached, and t_0 is the theoretical age at zero length. In LBB, the analytic framework is not based on absolute rates of growth and mortality, but on natural mortality rate relative to the rate by which L_{inf} is approached (M/k) and fishing mortality rate relative to somatic growth rate (F/k). In this way, mean relative fishing mortality (F/M) and current biomass relative to unfished biomass (B/B_0) can be estimated.

First, LBB estimates the L_{inf} (VB asymptotic length), the L_c (length at which 50% of the individuals are retained by the gear), and the mean of M/k and F/k over the past years. The user can introduce an estimate of L_{inf} if available as an informative prior, decreasing the uncertainty of the results. With these parameters, the relative stock size can be calculated in the form of biomass depletion (B/B_0). The length L_{c_opt} can also be calculated. This length determines the catch length (L_c) value that would result in the optimal length (L_{opt}) becoming the mean length in the catch, with the highest catch and biomass for the respective fishing mortality and a minimized impact on size structure (Froese *et al.*, 2016). Assuming L_c=L_{c_opt} and F/M=1, a proxy for the relative biomass that can produce the maximum sustainable yield (B_{MSY}) can also be calculated. The LBB provides two sets of output parameters: the median across years, and for the last year only (current state).

Four models were developed with this method for each dataset. The length at 50% maturity (L_{m50}) was set based on previous reports (Ramos & Winter, 2022) and fixed at 67 cm for all the models. The L_{inf} was estimated by the model using default LBB prior for model 1 and based on previous reports (Ramos & Winter, 2022) for models 2 and 4, and based on the *FishLife* package (Thorson *et al.*, 2023) for model 3, to create non-default priors. The M/k prior was based on the *FishLife* package for model 3, and based on previous reports (Ramos & Winter, 2022) for model 4 as non-default priors. Details of the priors are shown in Table 1.

Table 1. Priors defined for the LBB models. L_{inf}: asymptotic length for the BV equation; M/k: relationship between natural mortality and the rate by which L_{inf} is approached; L_{m50}: length at 50% maturity.

LBB	L_{inf}	M/k	L_{m50}
1	default	default	NA
2	144	default	67
3	131	1.66	67
4	144	2	67

LB-SPR

The LB-SPR method (Hordyk *et al.*, 2015a) is based on the idea that the size structure and the spawning potential ratio (SPR) of an exploited population depend on the ratio of fishing mortality to natural mortality (F/M), as well as the M/k and L_m/L_{inf} ratios (where M is the natural mortality rate, k is the VB growth rate, L_m is the size at maturity, and L_{inf} is the asymptotic VB size; Hordyk *et al.*, 2015b). The inputs for the LB-SPR model include the M/k ratio, the mean asymptotic length (L_{inf}), the variability in length-at-age (CVL_{inf}), which is difficult to estimate without good data and is often assumed to be 10%, and a description of the maturity schedule, given as $L_{50\%}$ and $L_{95\%}$, the sizes at which 50% and 95% of the population are mature. Using assumed values for M/k and L_{inf}, along with size composition data from a fished stock, the LB-SPR model applies maximum likelihood methods to estimate both the selectivity curve —assumed to follow a logistic shape defined by selectivity-at-length parameters SL_{50} and SL_{95}— and the relative fishing mortality (F/M), which are then used to calculate the SPR (Hordyk *et al.*, 2015a,b).

SPR estimates mainly depend on the size of the fish in the sample compared to the size at maturity and the asymptotic length (L_{inf}). In simple terms, if many fish in the sample grow to sizes close to L_{inf}, the estimated SPR will be high. On the other hand, if most fish are not much larger than the size of maturity, the estimated SPR will be low. The F/M ratio has been often used as a biological reference point with F_{MSY} = 0.87M considered as a reasonable approximation for teleost (Zhou *et al.*, 2012). However, sensitivity tests using the LB-SPR method (Hordyk *et al.*, 2015a) show that when fishing pressure is high, the method does not clearly separate values of F/M or selectivity, but it still gives reliable SPR estimates. This happens because the relationship between F/M and SPR is asymptotic, and determined by selectivity parameters. Thus, at high fishing pressure many different F/M and selectivity values can give similar SPR values. However, the SPR estimate is strongly affected by the size of the largest fish in the sample (Prince *et al.*, 2015).

The LB-SPR model, like other length-based methods, assumes that the stock is in equilibrium and relies on several key assumptions: (i) asymptotic selectivity, (ii) growth follows the VB equation, (iii) the same growth curve can describe both sexes and have equal catchability, or female data can be used, (iv) length-at-age is normally distributed, (v) natural mortality rates are constant among adults, and (vi) growth rates do not vary across cohorts within a stock. Simulation tests (Hordyk *et al.*, 2015a) show the model is most sensitive to underestimates of the asymptotic length (L_{inf}) and to sudden changes in recruitment. The LB-SPR method offers a practical, evidence-based tool for generating preliminary stock status estimates and guiding long-term data collection to support future assessments (Prince *et al.*, 2015).

The spawning potential ratio (SPR) of a stock is the proportion of the unfished reproductive potential left at a given level of fishing pressure (Goodyear, 1993). By definition, SPR of an unexploited stock equals 100%, and 0% if a stock has no spawning (no mature fish in the stock). The fishing mortality rate that results in a SPR=40% is considered risk adverse for many species (Clark, 2002), and a suitable reference point for a given stock.

For this report, three models using different life-history input parameters (based on different sources) were carried out for each dataset, with the aim to evidence the sensibility of the model to the input parameters. The input parameters are used by the model as fixed values. For all the models, lengths at 50% and 95% maturity were based on the previous report (Ramos & Winter, 2022). The relationship between natural mortality and the rate by which L_{inf} is approached (M/k) was based on the *Fishlife* package (Thorson *et al.*, 2023) for models 1 and 3, and taken from local literature (Ramos & Winter, 2022) for model 2. The steepness (*h*), introduced by Beverton & Holt (1957), is a parameter that can be included in the model. It is defined as the proportion of equilibrium unexploited recruitment produced by 20% of unexploited spawning stock size (Mace & Doonan, 1988). As the population being subject to stock assessment is currently being exploited, it becomes impossible to measure this parameter. For this reason, estimations based on life-history traits of the species were developed but with uncertain reliability (Lee *et al.*, 2012); this parameter was included only in models 2 and 3, and was based on the *FishLife* package (Thorson *et al.*, 2023). Details of the input parameters included in the models are shown in Table 2.

Table 2. Input parameters included in the LBSPR models. Linf: asymptotic length for the BV equation; M/k: relationship between natural mortality and the rate by which L_{inf} is approached; L_{50} and L_{95}: length at 50% and 95% maturity; *h*: steepness.

LBSPR	L_{inf}	L_{50}	L_{95}	M/k	*h*
1	144	67	80	1.66	NULL
2	144	67	80	2	0.479
3	131	67	80	1.66	0.479

Size-structure data

For this report, kingclip catch length frequencies were extracted from the FIFD groundfish surveys and from the commercial fishery data. A group of models was developed for each survey (February and July) and for the commercial fishery. Only the surveys using the same cod-end mesh size were included in the analysis. For the February surveys, the years 2010, 2019, 2020, 2021, 2022, 2023, and 2024 were included. For the July surveys, the included years were 2020, 2022, 2023, and 2024. The commercial fishery data was extracted for the period 2004-2024; in the earlier years, samples were sporadic. A total of 14,277 fish were measured in the February groundfish surveys, ranging in size from 32 cm to 153 cm. In the July surveys, 4,053 fish were measured, ranging from 35 cm to 119 cm. A total of 120,079 fish were measured from the commercial fishery, ranging in size from 10 cm to 153 cm. Length frequency samples were expanded to the total catch of the sampled trawl and all individuals were included. The expanded length-frequency histograms are shown in Figures A1, A2 and A3.

YPR

In this analysis we are only interested in the dynamics of a cohort that has already recruited to the population. In this scenario, the value of the number of recruits is arbitrary, as the dynamics of the cohort are independent of this value. For simplicity, a value of 1 was assigned to the number of recruits, allowing to track a single recruit in a per recruit analysis. There is no need to explicitly model egg production of survival to recruitment. Two main indicators are of interest for this analysis. The first one is the yield per recruit (*YPR*), which refers to the total catch accumulated from when the animals recruit to the population, until the final individual dies. It depends on the biomass of the cohort at a given age, which is the numbers at age *a* (N_a) multiplied by the weight at age (w_a), and the harvest strategy used, which is the exploitation rate (u) multiplied by a vulnerability pattern at age (v_a):

$$YPR = \sum_a u v_a N_a w_a$$

While this analysis may not explicitly assess the impact of fishing on future generations, it can still evaluate the changes in biomass as the cohort approaches maturity under a given harvest strategy. If the harvest strategy results in few individuals reaching maturity, it is most likely that future recruitment will be compromised, and the population would be unsustainable in the long term. The spawning biomass per recruit (SBPR) is the cumulative sum of biomass (or N_a times w_a) of animals that survive to maturity ($m_a N_a$), throughout the lifespan of the cohort:

$$SBPR = \sum_a m_a N_a w_a$$

Per recruit quantities are affected by both exploitation rate and by vulnerability at length. This type of analysis allows us to evaluate the effect of different harvest strategies, by changing the vulnerability and exploitation rates.

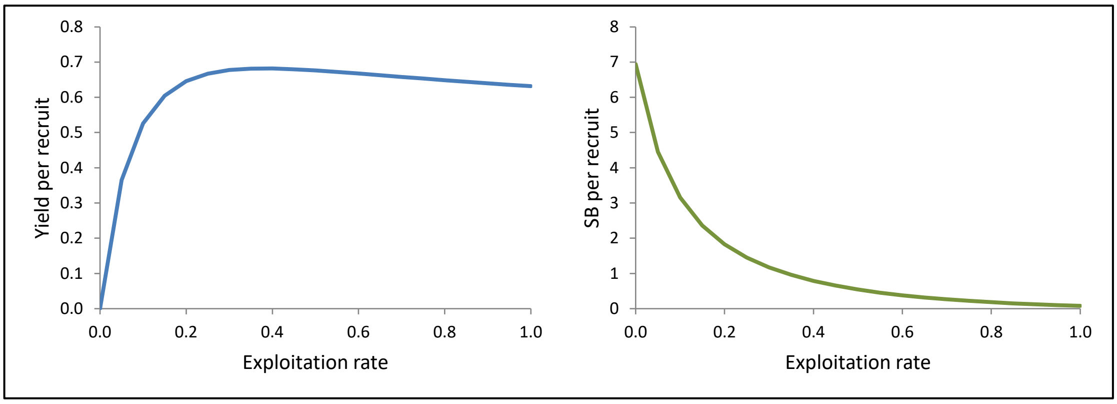

Figure 1. Examples of yield per recruit and spawning biomass per recruit curves in response to different exploitation rates.

A typical method of evaluating a harvest strategy is to first fix the vulnerability by age, and then observe how yield and spawning biomass per recruit change given different exploitation rates (Figure 1). Higher exploitation rates will result in lower numbers of animals that can spawn. The yield of the cohort increases with the exploitation rate until a point at which the intensity of fishing no longer produces significant changes in the biomass that can be harvest from the cohort.

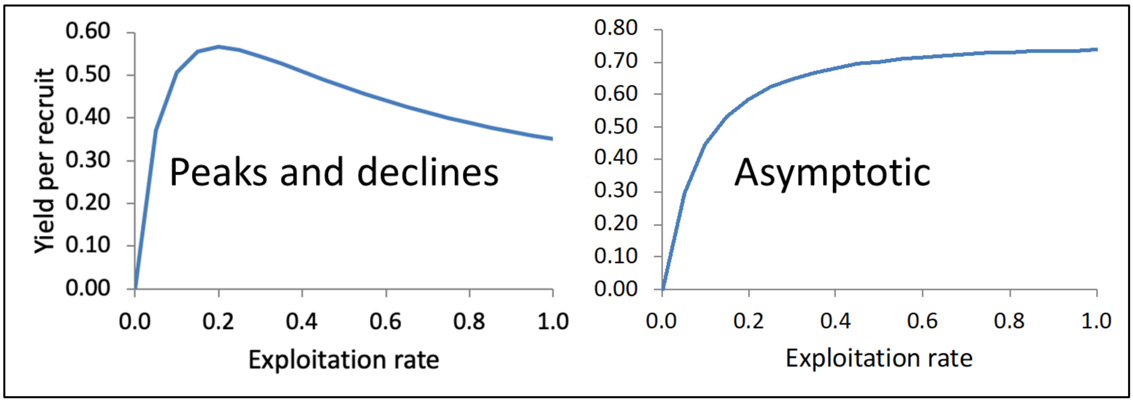

Figure 2. Examples of yield per recruit shape curves in response to different exploitation rates.

There are two common shapes of the yield per recruit curve (Figure 2). A curve that peaks and declines, happens when the individuals are exploited before they reach maturity and growth slows down. This implies that, if the cohort is exploited at too high a rate, a large proportion of the individuals will not develop their growth potential in biomass. An asymptotic relationship occurs when individuals become vulnerable to exploitation only after somatic growth slows. The yield obtained from this cohort increases with increasing exploitation rates, as uncaught individuals would simply end up dying from natural mortality.

The curves derived from these per recruit analyses allow to calculate useful quantities for management (reference points). It is generally accepted that, to maintain a biologically sustainable population, exploitation rates should not reduce the spawning biomass to more than 40% of the spawning biomass in an unfished state. The fishing mortality at which the spawning biomass per recruit is 40% of the unfished spawning biomass per recruit is known as $F_{40\%}$. Another reference point is the F_{max}; the exploitation rate that maximises yield per recruit. This reference point does not exist when the YPR curve is asymptotic, since that maximum occurs when the exploitation rate is 1. This reference point only makes sense when the management is not worried about maintaining a minimum spawning biomass to guarantee future recruitment. For example, it can be used when recruitment is highly dependent on environmental conditions or in metapopulations, where the exploitation of a sink subpopulation has to be regulated. In general, F_{max} is never used as a target reference point, but can instead be used as a maximum rate of exploitation, or an upper limit. In the 1990s, the general consensus found that fishing at F_{max} still led to over-exploitation of the resource (FAO, 1995).

The YPR method requires life-history parameters of the species and selectivity-at-length as inputs. Life-history parameters of the species related with the Von Bertalanffy curve (L_{inf} = 144 cm, k = 0.0872, t_0 = -0.3801) and the natural mortality (M = 0.1793) were extracted from the previous reports (Ramos & Winter, 2022), and the parameters of the length-weight equation (a = 0.0016, b = 3.2284) were extracted from the 2024 FIFD Bulletin (Falkland Islands Government, 2024).

A set of selectivity lengths were selected based on the estimations for the last year (2024) from the LBB and LBSPR methods performed before. The estimated lengths at 50% and 95% selectivity for both approaches (LBB and LBSPR) were averaged to obtain the average selectivity length. The analysis was then performed using the averaged length-based model results. A YPR approach was done separately for February survey, July survey and commercial fishery data. The F_{max} and $F_{40\%}$ were calculated. Further, a contour plot with a range of selectivity lengths was performed to detect the length at 50% selectivity that can increase the YPR with the highest fishing mortality, and then a new YPR analysis was done to detect the $F_{40\%}$ and F_{max} with the selected selectivity length.

Results

LBB

For the February surveys, the estimates of the optimal catch length ranged between 75 cm (LBB1) and 93 cm (LBB2) across the years. The ratio between fishing mortality and natural mortality (F/M) ranged between 2.27 (LBB1) and 4.93 (LBB2), and the ratio between the biomass and the virgin biomass ranged between 0.069 (LBB2) and 0.18 (LBB1; Table 3).

For the July surveys, the estimates of the optimal catch length ranged between 76 cm (LBB1) and 97 cm (LBB2) across the years. The ratio between fishing mortality and natural mortality (F/M) ranged between 1.5 (LBB1) and 4.69 (LBB2), and the ratio between the biomass and the virgin biomass ranged between 0.064 (LBB2) and 0.26 (LBB1; Table 3).

For the commercial fishery (2004-2024), the estimations of the optimal catch length ranged between 79 cm (LBB1) and 88 cm (LBB2) across the years. The ratio between fishing mortality and natural mortality (F/M) ranged between 1.61 (LBB3) and 3.07 (LBB2), and the ratio between the biomass and the virgin biomass ranged between 0.094 (LBB2) and 0.2 (LBB3; Table 3).

Table 3. LBB estimates across years for the February and July surveys, and for the commercial fishery information. The median is presented in bold and the credible interval between brackets (when available). L_{inf}: asymptotic length from the BV equation; L_{opt}: length where unexploited cohort biomass is maximum; L_{c_opt}: length at first capture that maximizes catch and biomass; M/k: ratio of natural mortality to VB growth rate; F/M: ratio of fishing mortality to natural mortality; B/B_0: ratio of the present to the virgin biomass.

		LBB1	LBB2	LBB3	LBB4
February	L_{inf}	**121** (119-123)	**142** (140-145)	**132** (130-134)	**143** (141-145)
	L_{opt}	**83**	**99**	**86**	**86**
	L_{c_opt}	**75**	**93**	**79**	**80**
	M/k	**1.36** (1.13-1.63)	**1.32** (1.03-1.69)	**1.62** (1.46-1.74)	**1.95** (1.82-2.09)
	F/M	**2.27** (1.76-3.05)	**4.93** (3.77-6.37)	**3.31** (2.76-3.74)	**3.25** (2.85-3.81)
	B/B_0	**0.18** (0.12-0.23)	**0.069** (0.05-0.088)	**0.12** (0.092-0.15)	**0.097** (0.079-0.11)
July	L_{inf}	**111** (110-113)	**143** (141-146)	**131** (128-133)	**143** (140-145)
	L_{opt}	**76**	**97**	**85**	**86**
	L_{c_opt}	**66**	**91**	**78**	**80**
	M/k	**1.37** (1.14-1.64)	**1.44** (1.16-1.71)	**1.63** (1.48-1.78)	**1.98** (1.85-2.11)
	F/M	**1.5** (1.01-2.18)	**4.69** (3.78-6.04)	**3.09** (2.67-3.6)	**3.4** (2.96-3.81)
	B/B_0	**0.26** (0.13-0.39)	**0.064** (0.044-0.09)	**0.12** (0.097-0.15)	**0.1** (0.083-0.12)
Fisheries	L_{inf}	**127** (125-129)	**140** (139-143)	**131** (130-133)	**141** (140-144)
	L_{opt}	**88**	**96**	**85**	**85**
	L_{c_opt}	**79**	**88**	**75**	**74**
	M/k	**1.34** (1.06-1.6)	**1.38** (1.09-1.59)	**1.6** (1.49-1.75)	**1.96** (1.83-2.1)
	F/M	**2.33** (1.34-3.22)	**3.07** (2.19-4.4)	**1.61** (1.39-1.87)	**1.65** (1.44-1.95)
	B/B_0	**0.16** (0.11-0.25)	**0.094** (0.068-0.13)	**0.2** (0.16-0.24)	**0.18** (0.15-0.22)

For the final year (2024), the median length at 50% selectivity ranged between 69.1 cm (LBB1) and 70.6 cm (LBB4) for the February surveys length compositions, 58.4 cm (LBB1) and 60.6 cm (LBB4) for the July surveys, and 53.8 cm (LBB1) and 54.4 cm (LBB2, LBB4) for the commercial fishery. The percentage of mature individuals in the catch was 64% for the February surveys, 47% for the July surveys, and 39% for the commercial fishery. This value was not calculated for LBB1, as the L50 was not included as a prior. The ratio between the fishing mortality and the natural mortality ranged between 2.3 (LBB1) and 4.9 (LBB2) for the February surveys, 1.5 (LBB1) and 4.4 (LBB2) for the July surveys, and 1.4 (LBB1) and 2.5 (LBB2) for the commercial fishery. The ratio between the biomass in 2024 and the virgin biomass ranged between 0.071 (LBB2) and 0.19 (LBB1) for the February surveys, 0.064 (LBB2) and 0.26 (LBB1) for the July surveys, and between 0.12 (LBB2) and 0.23 (LBB2) for the commercial fishery. The ratio between the biomass in 2024 and the biomass at MSY ranged between 0.19

(LBB2) and 0.5 (LBB1) for the February surveys, 0.18 (LBB2) and 0.71 (LBB1) for the July surveys, and between 0.32 (LBB2) and 0.63 (LBB2) for the commercial fishery. Detailed results are shown in Table 4.

Table 4. LBB estimates for the final year (2024) for the February and July surveys, and for the commercial fishery information. The median is presented in bold and the credible interval between brackets, when available. L_{c50}, L_{c95}: length of catch at 50% and 95%; L_c/L_{c_opt}: ratio between the length of catch and the optimal catch length; L_{95th}/L_{inf}: ratio between the catch length of the last 5% of the sizes and the VB asymptotic length; %mature: percentage of mature individuals in the catch composition; F/M ratio between the fishing and natural mortality; B/B_0: ratio between the present and the virgin biomass; B/B_{MSY}: ratio between the present biomass and the biomass at MSY.

		LBB1	LBB2	LBB3	LBB4
February	L_{c50}	**69.1** (68.3-69.9)	**70.4** (69.71.3)	**69.8** (68.5-70.8)	**70.6** (69.9-71.4)
	L_{c95}	**87.2**	**89.1**	**88.1**	**89.1**
	L_c/L_{c_opt}	**0.92**	**0.76**	**0.88**	**0.89**
	L_{95th}/L_{inf}	**0.91**	**0.82**	**0.91**	**0.82**
	%Mature	**NA**	**64**	**64**	**64**
	F/M	**2.3** (1.8-3.1)	**4.9** (3.8-6.4)	**3.3** (2.8-3.9)	**3.9** (3.3-4.4)
	B/B_0	**0.19** (0.13-0.26)	**0.071** (0.05-0.096)	**0.12** (0.092-0.15)	**0.097** (0.079-0.11)
	B/B_{MSY}	**0.5** (0.34-0.7)	**0.19** (0.13-0.26)	**0.33** (0.25-0.41)	**0.28** (0.23-0.33)
July	L_{c50}	**58.4** (57.8-59.2)	**60.5** (59.9-61.1)	**60** (59.4-60.7)	**60.6** (60-61.4)
	L_{c95}	**74.5**	**77**	**76.1**	**76.7**
	L_c/L_{c_opt}	**0.88**	**0.66**	**0.77**	**0.76**
	L_{95th}/L_{inf}	**0.54**	**0.8**	**0.88**	**0.8**
	%Mature	**NA**	**47**	**47**	**47**
	F/M	**1.5** (0.83-2.3)	**4.4** (3.3-6)	**1.9** (1.6-2.3)	**2.1** (1.9-2.5)
	B/B_0	**0.26** (0.12-0.46)	**0.064** (0.042-0.095)	**0.19** (0.15-0.24)	**0.16** (0.13-0.19)
	B/B_{MSY}	**0.71** (0.32-1.2)	**0.18** (0.11-0.26)	**0.52** (0.41-0.66)	**0.46** (0.38-0.55)
Fishery	L_{c50}	**53.8** (53.3-54.2)	**54.4** (54-54.7)	**54** (53.7-54.4)	**54.4** (54.1-54.8)
	L_{c95}	**65.5**	**66.4**	**66**	**66.3**
	L_c/L_{c_opt}	**0.68**	**0.62**	**0.72**	**0.73**
	L_{95th}/L_{inf}	**0.98**	**0.91**	**0.99**	**0.91**
	%Mature	**NA**	**39**	**39**	**39**
	F/M	**1.4** (1-1.8)	**2.5** (2-3.4)	**1.6** (1.4-1.9)	**1.7** (1.5-2.1)
	B/B_0	**0.23** (0.15-0.32)	**0.12** (0.085-0.17)	**0.2** (0.16-0.24)	**0.18** (0.15-0.22)
	B/B_{MSY}	**0.63** (0.4-0.86)	**0.32** (0.23-0.46)	**0.55** (0.45-0.66)	**0.51** (0.42-0.64)

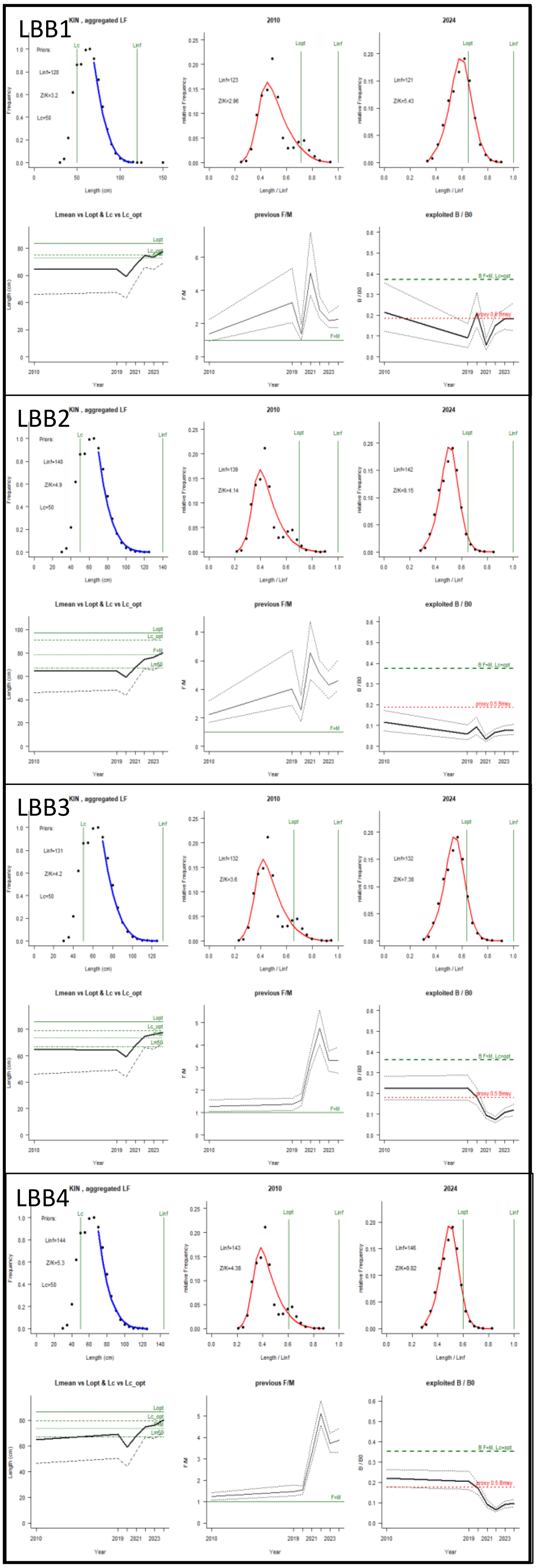

Figure 3. Model estimates for the February surveys. Each panel corresponds to a different model. Inside each panel, the upper left panel shows the accumulated LF data used to estimate priors for L_c, L_{inf} and Z/K. The upper middle and right panels show the LF data for the first and last year in the time series. The red curve shows the fit of the LBB master equation, which provides estimates of Z/K, M/K, F/K, L_c, and L_{inf}. From L_{inf} and M/K, L_{opt} is calculated and shown as reference. The lower left panel shows L_{mean} (bold black curve) relative to L_{opt}, and L_c (dashed black curve) relative to L_{c_opt}. The lower middle panel shows relative fishing pressure F/M (black curve), with approximate 95% confidence limits (dotted curves), with indication of the reference level where F = M (green horizontal line). The lower right panel shows relative biomass B/B_0 (black curve) with approximate 95% confidence limits (dotted black curves), with indication of a proxy for B_{msy} (green dashed line) and a proxy for 0.5 B_{msy} (red dotted line). Note the gap in surveys between the first year (2010) and the following (2019).

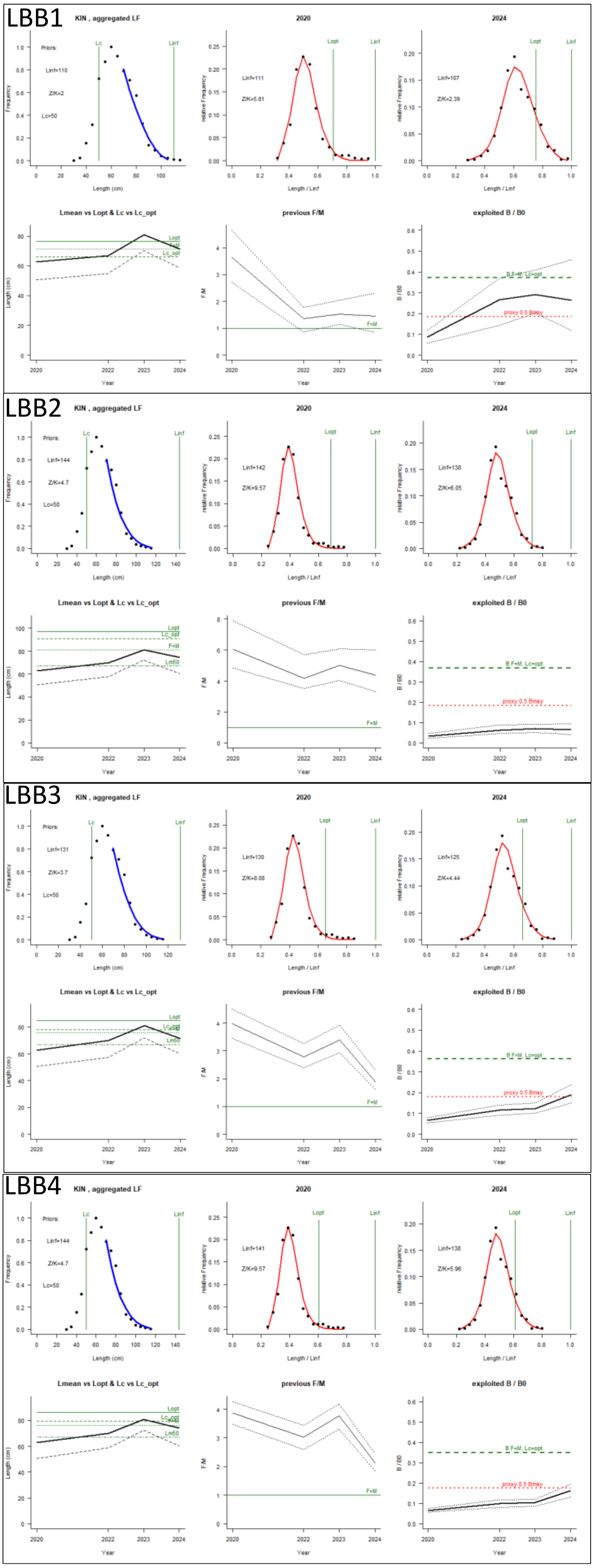

Figure 4. Model estimates for the July surveys. Each panel corresponds to a different model. Inside each panel, the upper left panel shows the accumulated LF data used to estimate priors for L_c, L_{inf} and Z/K. The upper middle and right panels show the LF data for the first and last year in the time series. The red curve shows the fit of the LBB master equation, which provides estimates of Z/K, M/K, F/K, L_c, and L_{inf}. From Linf and M/K, L_{opt} is calculated and shown as reference. The lower left panel shows L_{mean} (bold black curve) relative to L_{opt}, and L_c (dashed black curve) relative to L_{c_opt}. The lower middle panel shows relative fishing pressure F/M (black curve), with approximate 95% confidence limits (dotted curves), with indication of the reference level where F = M (green horizontal line). The lower right panel shows relative biomass B/B_0 (black curve) with approximate 95% confidence limits (dotted black curves), with indication of a proxy for B_{msy} (green dashed line) and a proxy for 0.5 B_{msy} (red dotted line). Note the gap in surveys between the first year (2020) and the following (2022).

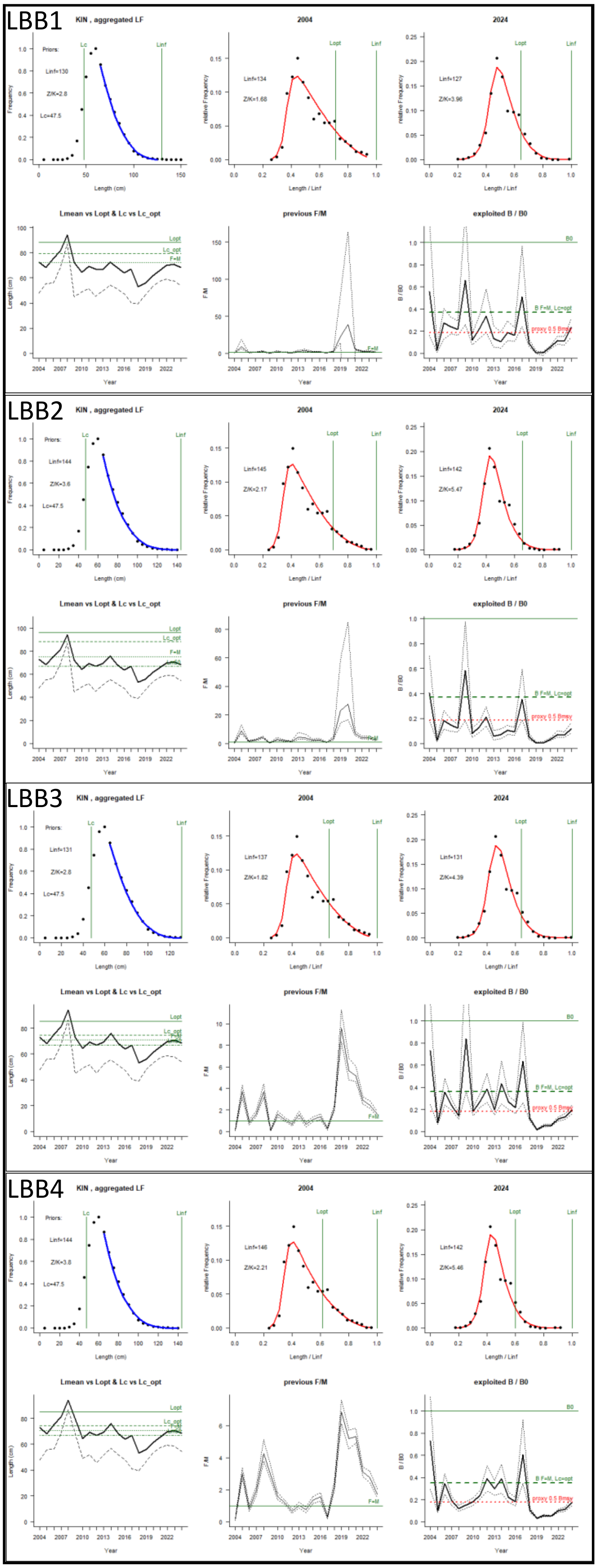

Figure 5. Model estimates for the industrial fisheries. Each panel corresponds to a different model. Inside each panel, the upper left panel shows the accumulated LF data used to estimate priors for L_c, Linf and Z/K. The upper middle and right panels show the LF data for the first and last year in the time series. The red curve shows the fit of the LBB master equation, which provides estimates of Z/K, M/K, F/K, L_c, and L_{inf}. From L_{inf} and M/K, L_{opt} is calculated and shown as reference. The lower left panel shows L_{mean} (bold black curve) relative to L_{opt}, and L_c (dashed black curve) relative to L_{c_opt}. The lower middle panel shows relative fishing pressure F/M (black curve), with approximate 95% confidence limits (dotted curves), with indication of the reference level where F = M (green horizontal line). The lower right panel shows relative biomass B/B_0 (black curve) with approximate 95% confidence limits (dotted black curves), with indication of a proxy for B_{msy} (green dashed line) and a proxy for 0.5 B_{msy} (red dotted line).

The trend for the catch length showed values consistently below the L_{c_opt} for all the models and with all the datasets (Figures 3-5). In the same way, the fishing mortality (F) was above the natural mortality (M) by many times, and the biomass was estimated to be below the MSY (Figures 3-5). The most optimistic scenario was estimated for model LBB1. In this scenario, the biomass was near (Figure 3) or above (Figures 4, 5) 0.5 of the B_{MSY}, but still below the B_{MSY}.

Moreover, the LBB method gives other indicators that are useful at the moment of management. Focusing in the commercial fishery data for 2024, the ratio between the catch length and the optimum catch length ranged between 0.62 and 0.73, the ratio of the length corresponding to the 95th percentile of the catch to the asymptotic length (L_{95th} /L_{inf}), that indicates how close the largest individuals in the catch are to the theoretical maximum length, ranged between 0.91 and 0.99, and the proportion of mature individuals in the catch was 39%.

LB-SPR

The median length at 50% selectivity across years ranged between 57.7 cm (LBSPR3) and 57.9 cm (LBSPR2) for the February surveys data, between 60.5 cm (LBSPR3) and 61.15 cm (LBSPR2) for the July surveys, and between 51.3 cm (LBSPR1,2) and 51.4 cm (LBSPR3) for the commercial fishery data. The ratio between the fishing mortality and the natural mortality (F/M) median, varied between 3.1 (LBSPR3) and 4.1 (LBSPR1) for the February surveys, between 3 (LBSPR2) and 4 (LBSPR1) for the July surveys, and between 2.3 (LBSPR2) and 3.5 (LBSPR3) for the commercial fishery. The estimated spawning potential ratio (SPR) ranged between 0.09 (LBSPR1) and 0.13 (LBSPR2-3) for the February surveys, between 0.1 (LBSPR1) and 0.13 (LBSPR2-3) for the July surveys, and between 0.1 (LBSPR1,3) and 0.15 (LBSPR2) for the commercial fishery.

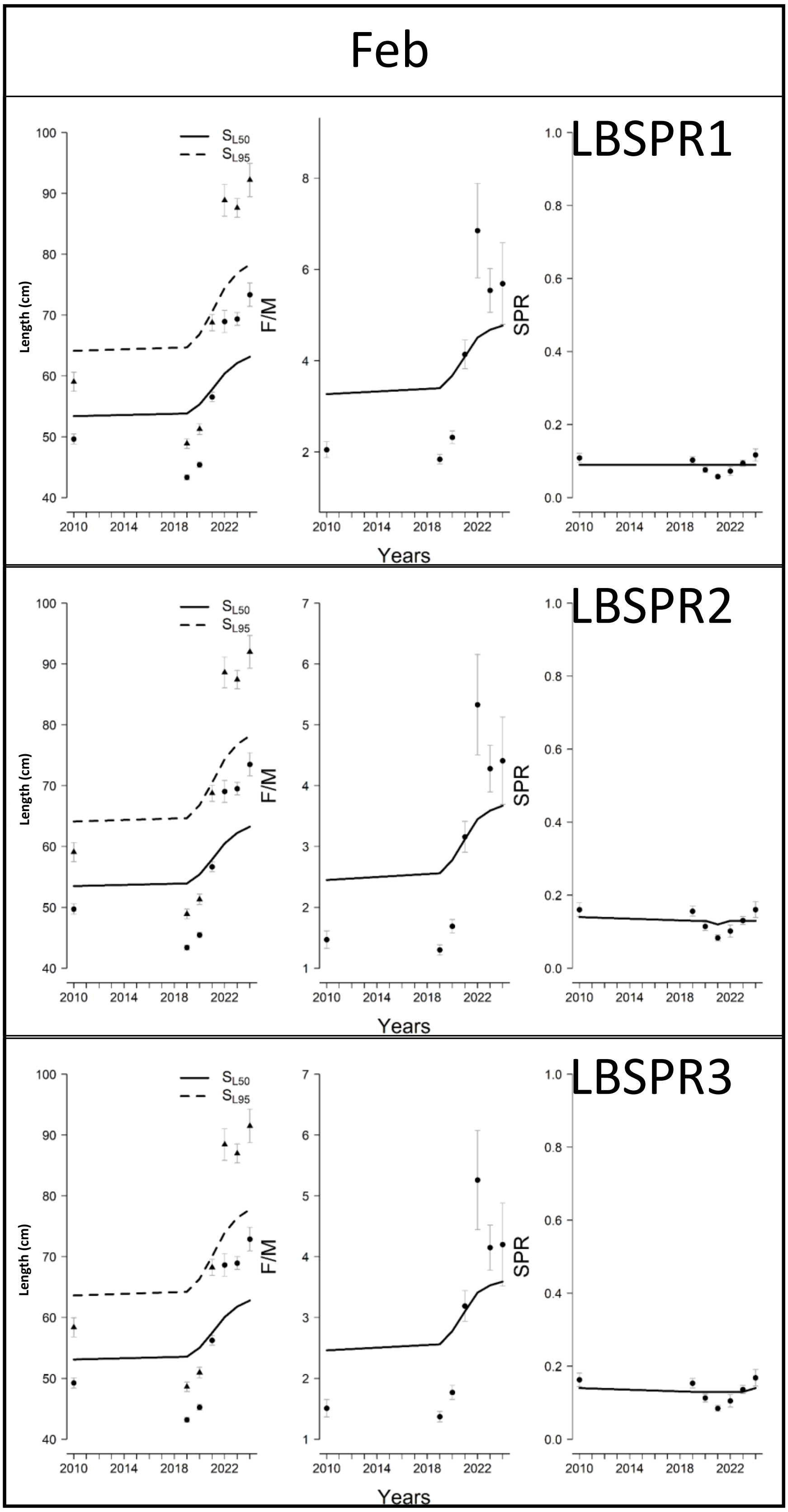

Figure 6. Estimated parameters (lines) for each model (rows) for the February survey data. Within each row, the left panel shows time-series of the estimated lengths at 50% and 95% selectivity (S_{L50}, S_{L95}), the middle panel shows the ratio of fishing mortality to natural mortality (F/M), and the right panel shows the spawning potential ratio (SPR). The dots indicate the raw data and the vertical bars the 95% confidence interval.

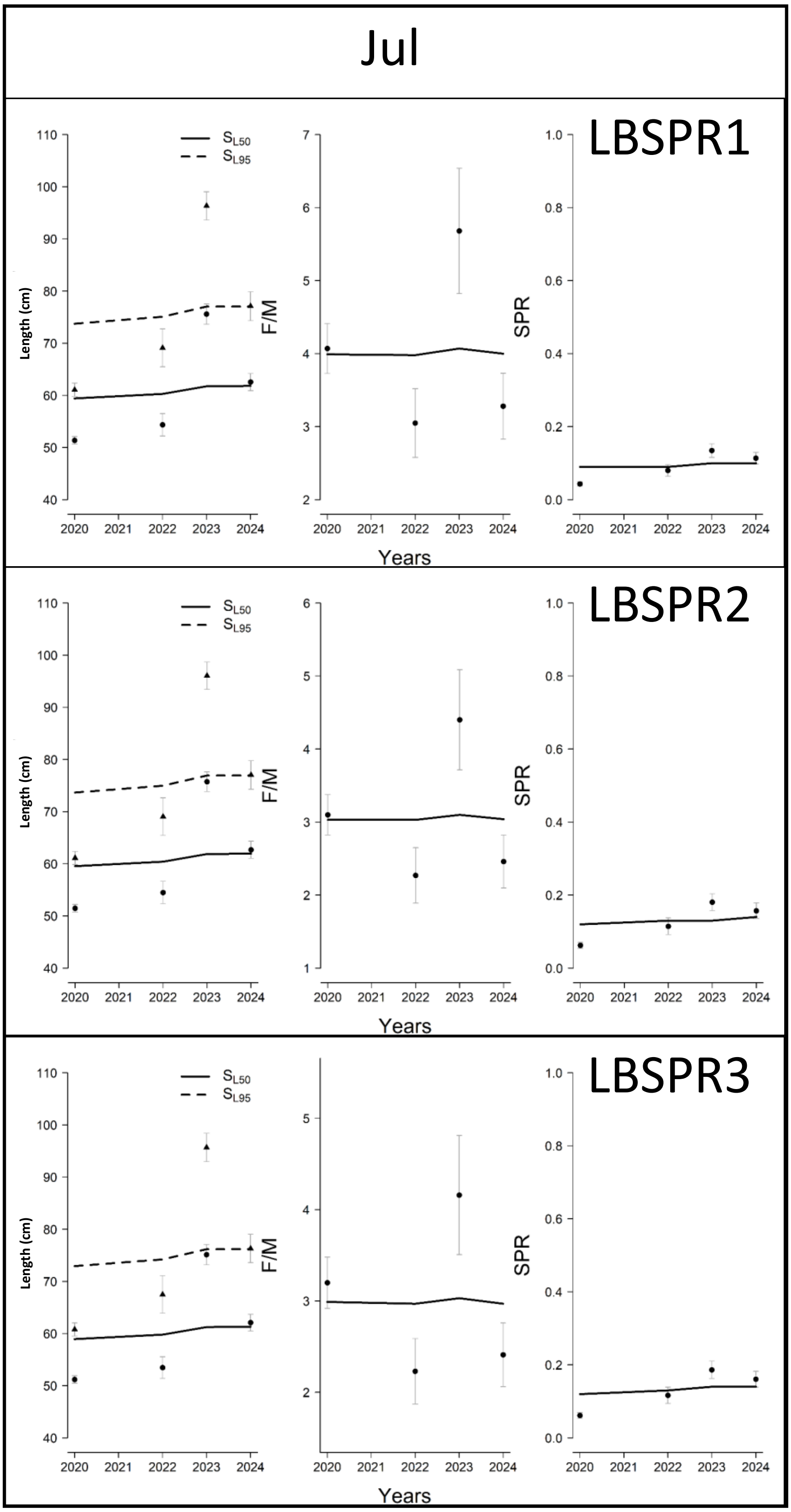

Figure 7. Estimated parameters (lines) for each model (rows) for the July survey data. Within each row, the left panel shows time-series of the estimated lengths at 50% and 95% selectivity (S_{L50}, S_{L95}), the middle panel shows the ratio of fishing mortality to natural mortality (F/M), and the right panel shows the spawning potential ratio (SPR). The dots indicate the raw data and the vertical bars the 95% confidence interval.

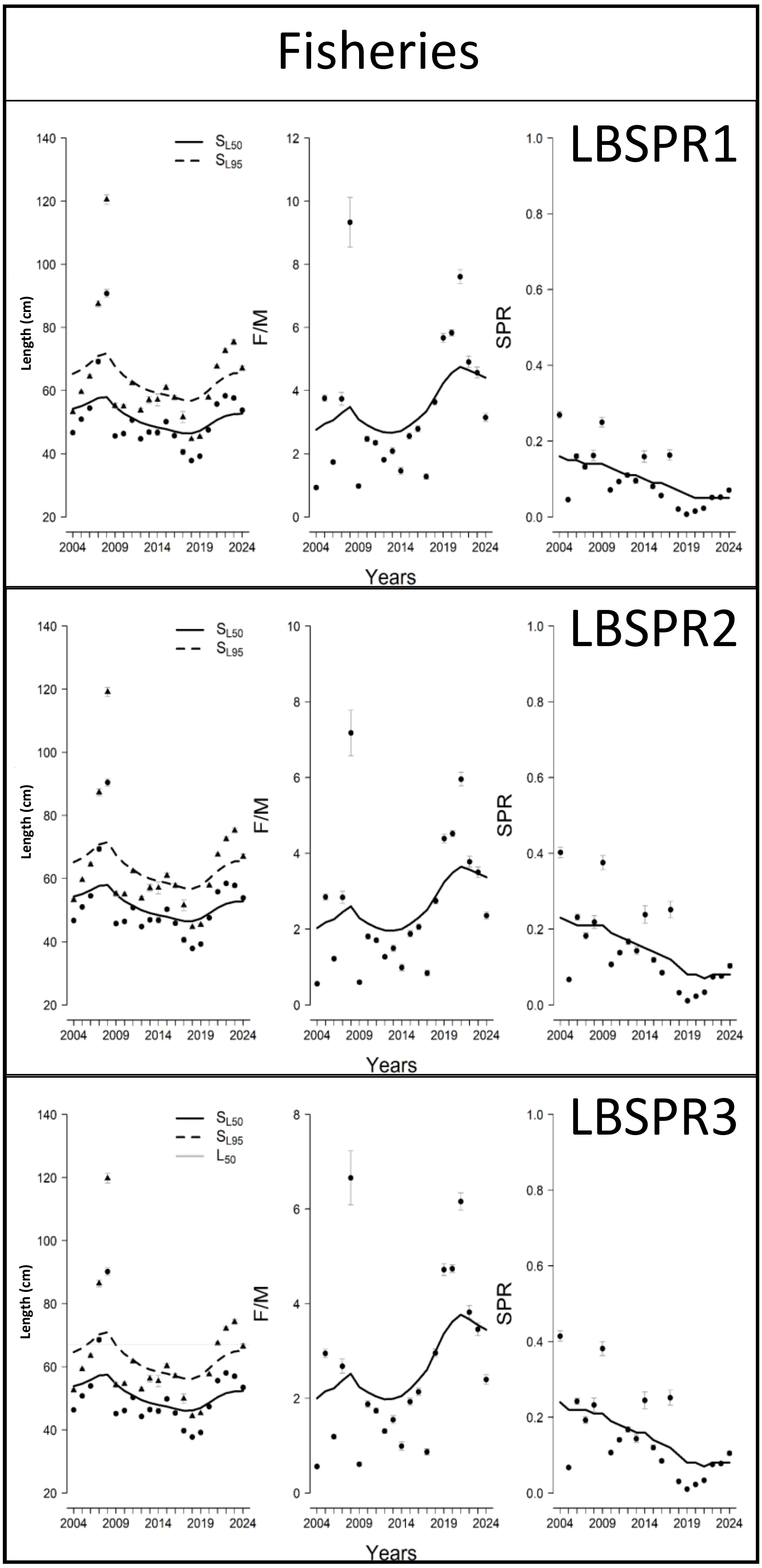

Figure 8. Estimated parameters (lines) for each model (rows) for the commercial fishery data. Within each row, the left panel shows time-series of the estimated lengths at 50% and 95% selectivity (S_{L50}, S_{L95}), the middle panel shows the ratio of fishing mortality to natural mortality (F/M), and the right panel shows the spawning potential ratio (SPR). The dots indicate the raw data and the vertical bars the 95% confidence interval.

For the last year (2024), the length at 50% selectivity ranged between 62.81 cm (LBSPR3) and 63.27 cm (LBSPR2) for the February surveys, between 61.33 cm (LBSPR3) and 61.95 cm (LBSPR2) for the July surveys, and between 52.70 cm (LBSPR1, 3) and 52.80 cm (LBSPR2) for the commercial fishery. The fishing vs. natural mortality ratio (F/M) ranged between 3.60 (LBSPR3) and 4.77 (LBSPR1) for the February surveys, between 2.97 (LBSPR3) and 4.00 (LBSPR1) for the July surveys, and between 3.37 (LBSPR3) and 4.41 (LBSPR1, 2) for the commercial fishery. The SPR ranged between 0.09 (LBSPR1) and 0.14 (LBSPR3) for the February surveys, between 0.10 (LBSPR1) and 0.14 (LBSPR2, 3) for the July surveys, and between 0.05 (LBSPR1, 3) and 0.08 (LBSPR2) for the commercial fishery. The yearly trend for selectivity length, F/M and SPR are shown in Figures 6, 7 and 8, and the estimated values in Tables A1, A2 and A3.

In all the models and for all the datasets, the estimated length at 50% selectivity was below the length at 50% maturity of the kingclip, meaning the fish are being caught before they reach their sexual maturity (Figures 9, 10, 11).

When comparing the observed *vs.* the expected size, for all the models and all the datasets, the observed size data shows a smaller size composition than the one that is expected for a population with a spawning potential ratio of 40% (Figures 12, 13, 14). Only the years 2004, 2006, 2012, 2014, and 2017 for the commercial fishery shows a similar size structure to the one expected at a SPR target of 40% (Figure 14).

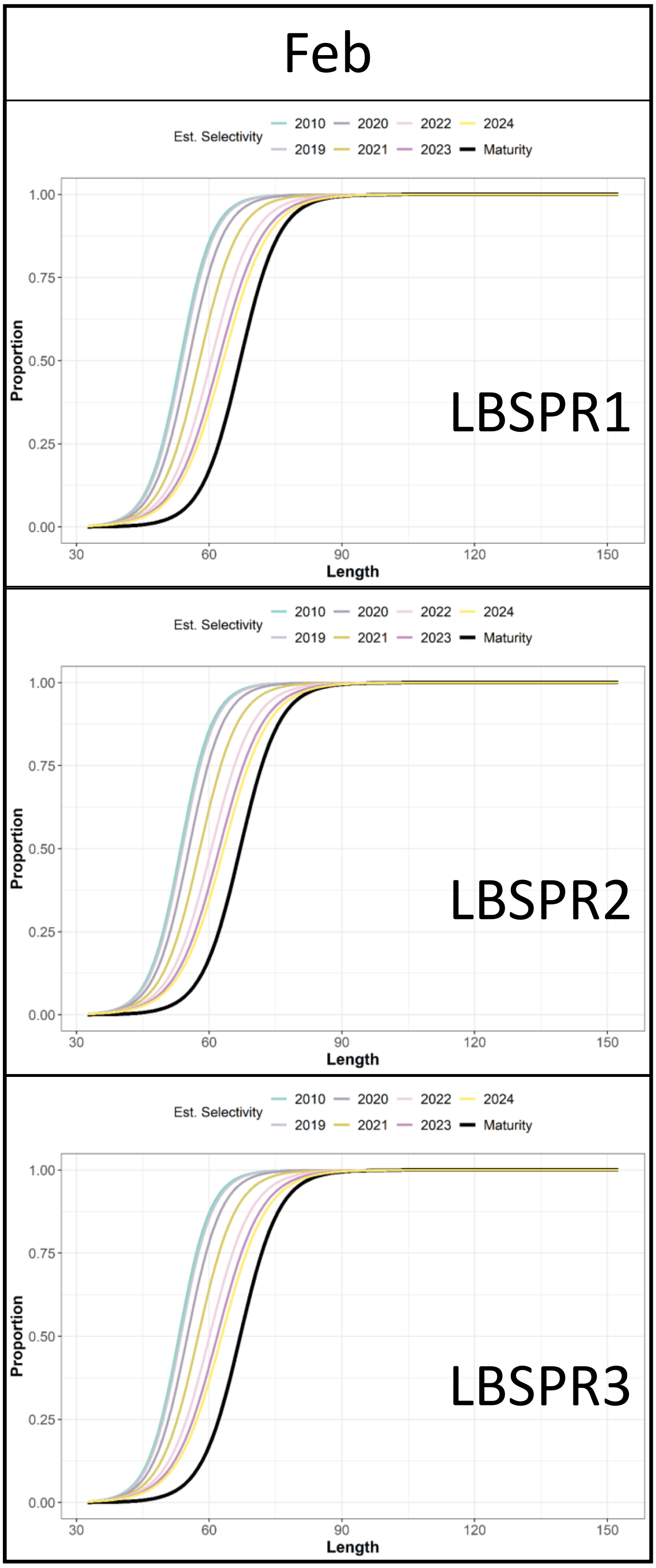

Figure 9. Specified maturity-at-length curve (bold black), and the estimated selectivity-at-length curve for each year (colours) for the February survey data. Rows correspond to the different models for the February data set.

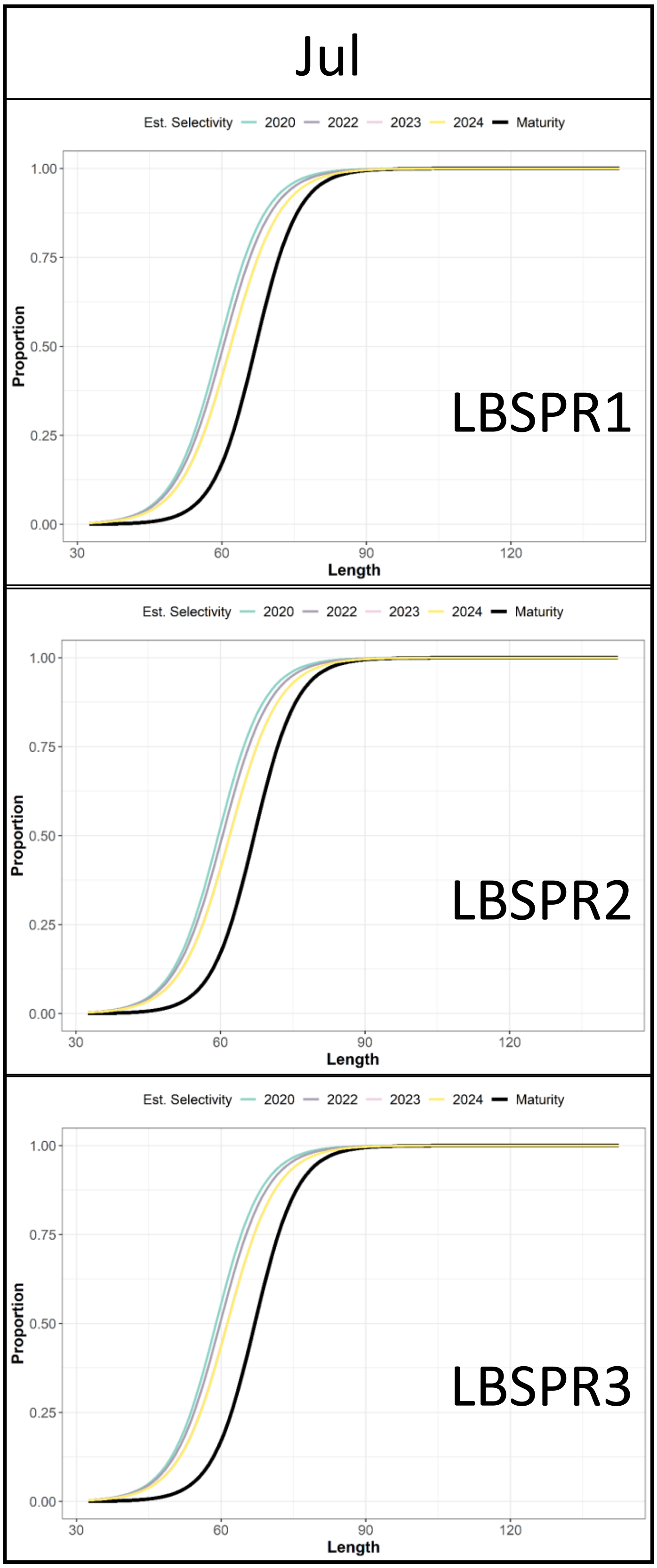

Figure 10. Specified maturity-at-length curve (bold black), and the estimated selectivity-at-length curve for each year (colours) for the July survey data. Rows correspond to the different models for the July data set.

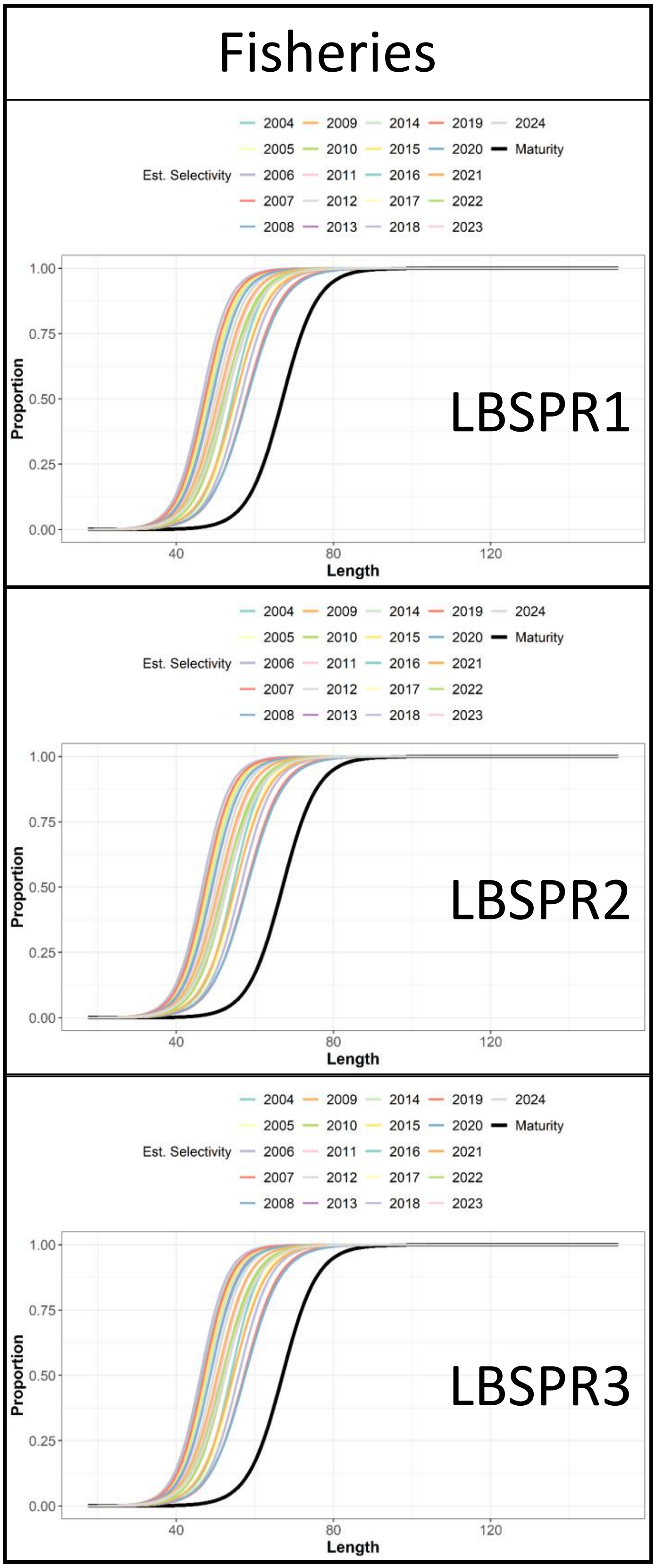

Figure 11. Specified maturity-at-length curve (bold black), and the estimated selectivity-at-length curve for each year (colours) for the commercial fishery data. Rows correspond to the different models for the commercial fishery data set.

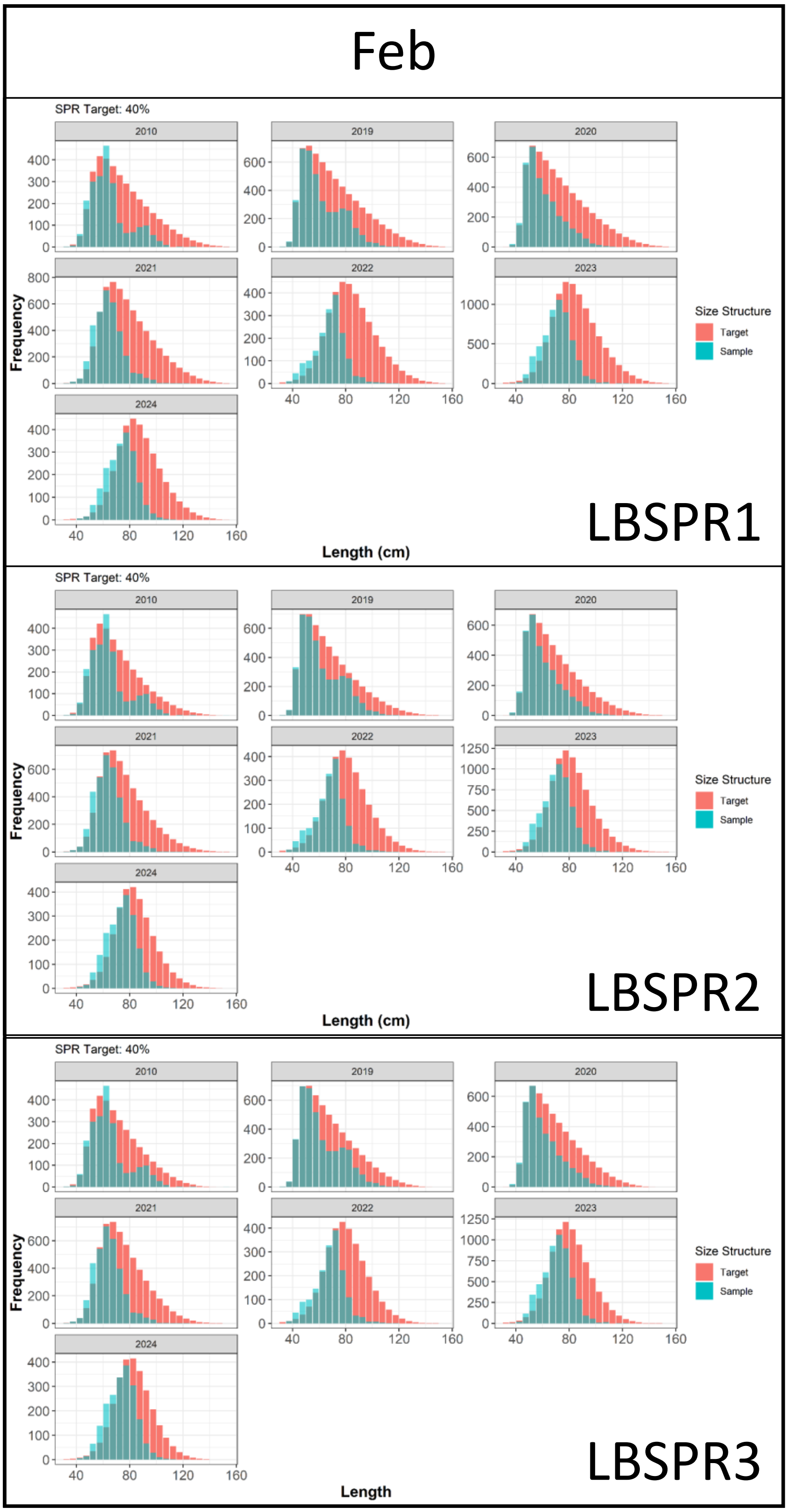

Figure 12. Comparison of observed size data (sample) with the expected size composition at a target SPR of 40% for each year of all the models (rows) of the February survey data.

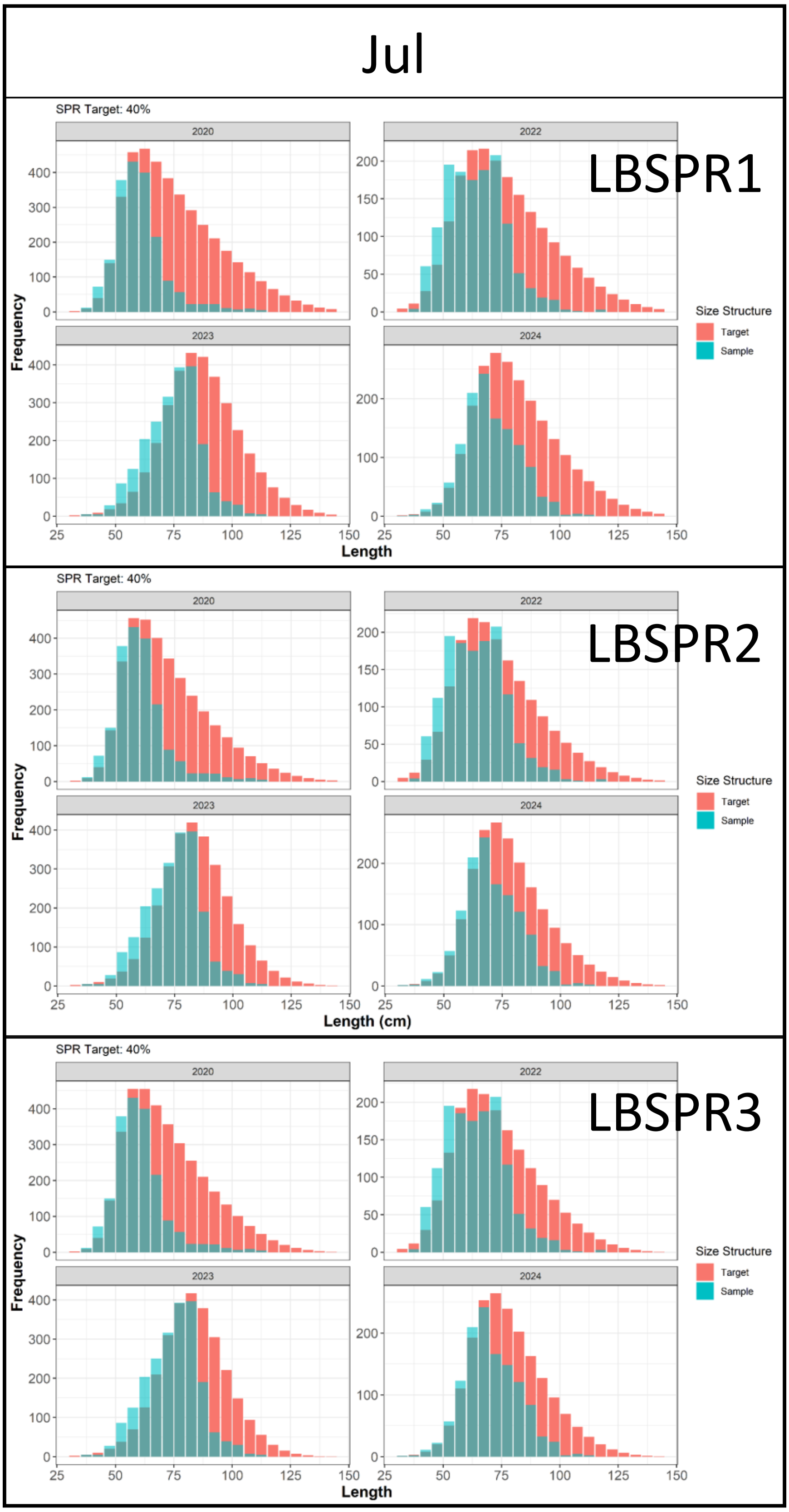

Figure 13. Comparison of observed size data (sample) with the expected size composition at a target SPR of 40% for each year of all the models (rows) of the February survey data.

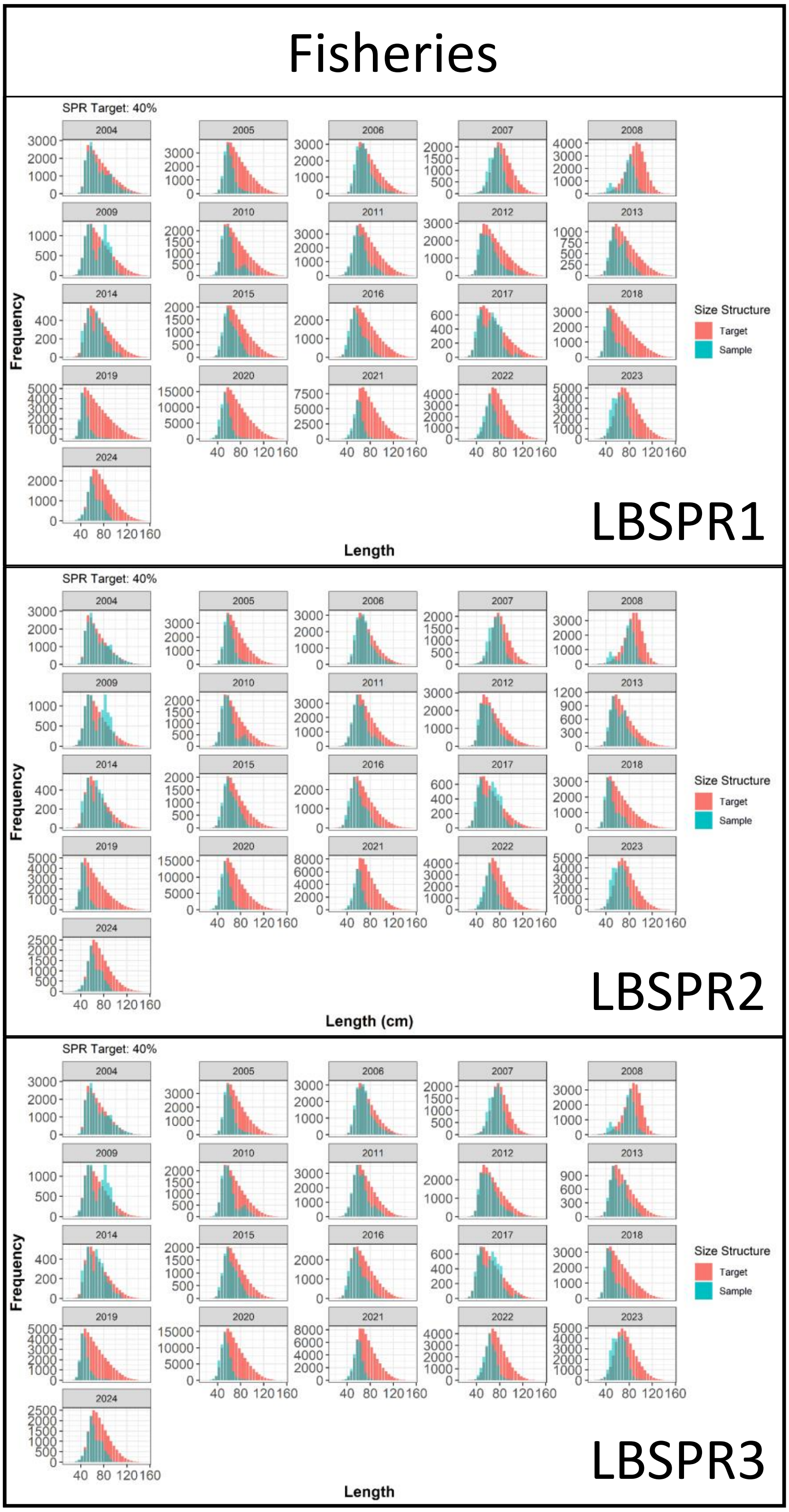

Figure 14. Comparison of observed size data (sample) with the expected size composition at a target SPR of 40% for each year of all the models (rows) of the commercial fishery data.

YPR

The selectivity lengths were set at $SL_{50\%}$ = 66.53 cm, $SL_{95\%}$ = 83.24 cm from the February survey results, $SL_{50\%}$ = 60.79 cm, $SL_{95\%}$ = 76.40 cm from the July survey results, and $SL_{50\%}$ = 53.44 cm, $SL_{95\%}$ = 65.85 cm from the commercial fishery results. In all the cases, the YPR curve shows a peak and decline shape, with a steeper peak and decline for the commercial fishery data (Figure 15). The estimated reference points for the February surveys were $F_{40\%}$ = 0.15, and F_{max} = 0.36; for the July surveys the estimations were $F_{40\%}$ = 0.13, and F_{max} = 0.30; for the commercial fishery data the estimations were $F_{40\%}$ = 0.11, and F_{max} = 0.24.

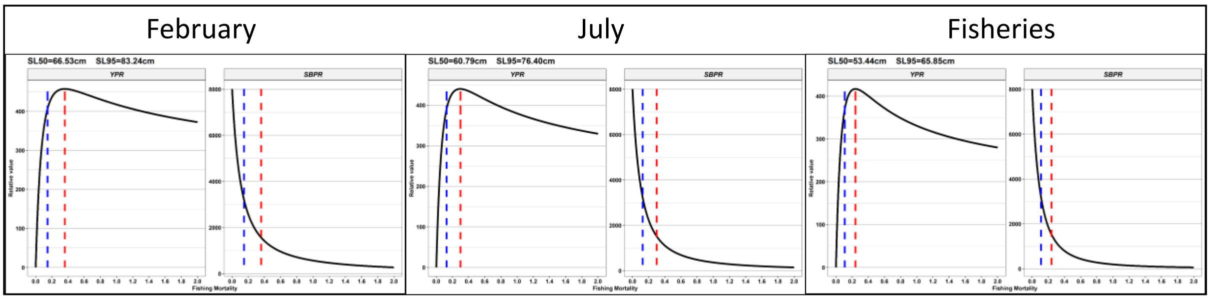

Figure 15. Yield per recruit analysis for the February and July surveys and the commercial fishery data. The blue dashed line represents the $F_{40\%}$ reference point, and the red dashed line represents the F_{max}.

The contour plot shows that the maximum yield could be achieved with selectivity lengths $SL_{50\%}$ close to 80 cm (Figure 16). With this value, a new YPR analysis was conducted, including $SL_{50\%}$ = 80 cm and $SL_{95\%}$ = 95 cm.

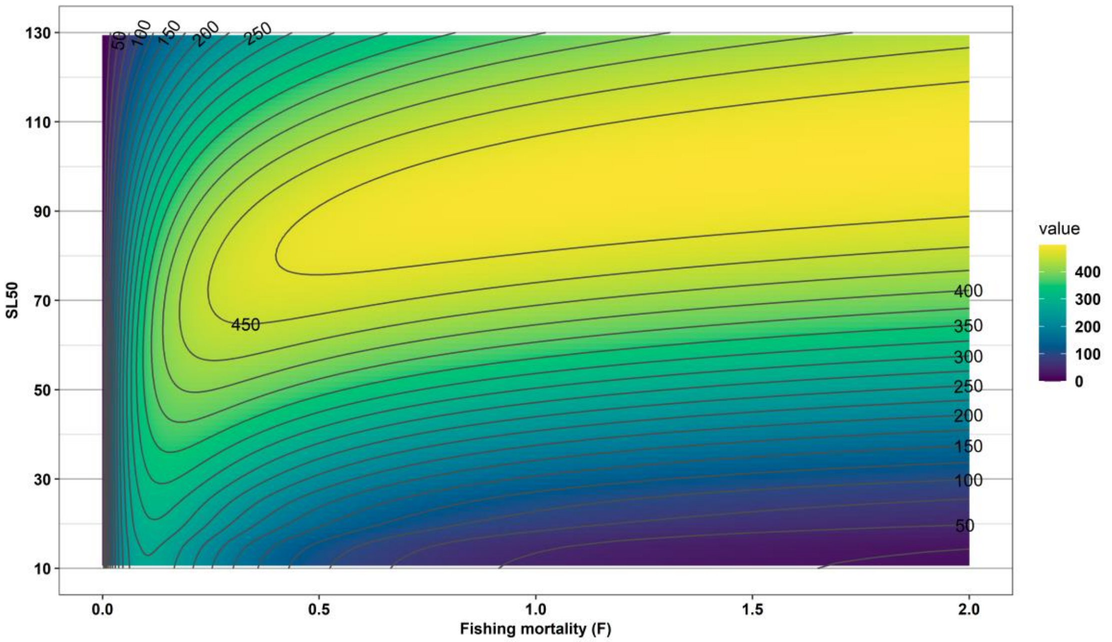

Figure 16. Contour plot of yield per recruit for different lengths at 50% selectivity (SL50) and fishing mortality (F). Values indicate the relative YPR.

If $SL_{50\%}$ = 80 cm and $SL_{95\%}$=95 cm is considered, then $F_{40\%}$ could be raised to 0.24 and F_{max} will be in the order of 0.7 (Figure 17).

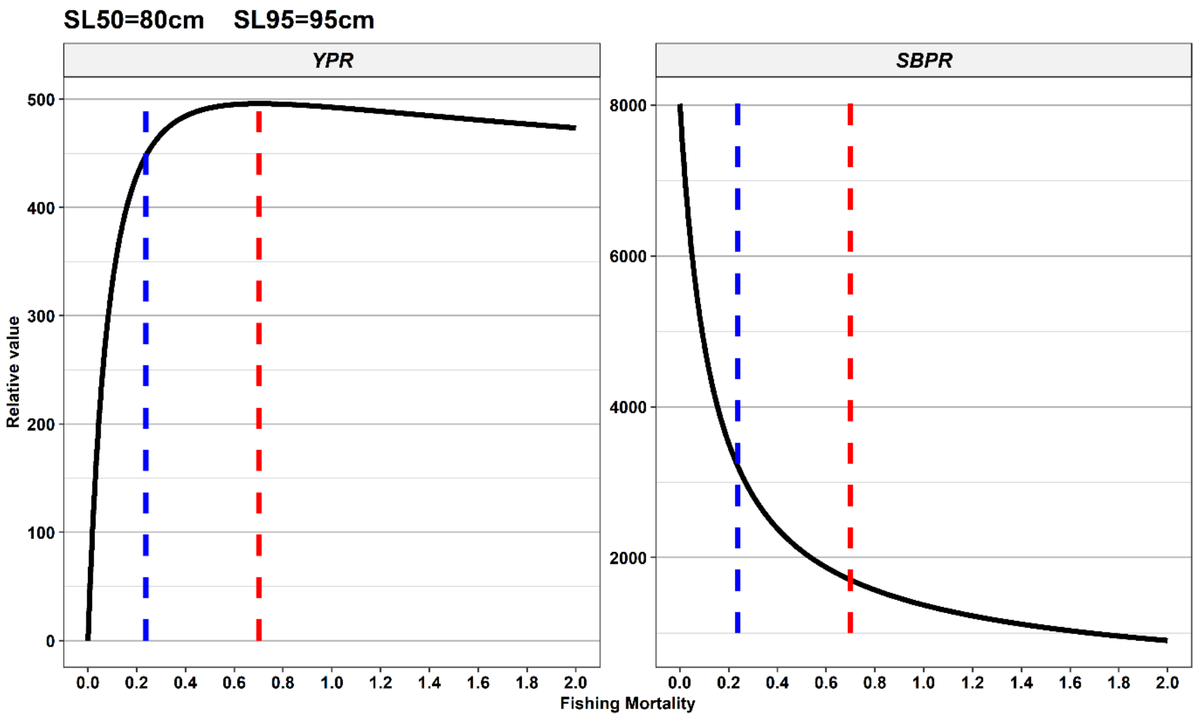

Figure 17. Yield per recruit analysis considering a selectivity length $SL_{50\%}$ at 80 cm and a $SL_{95\%}$ at 95 cm. The blue dashed line represents the $F_{40\%}$ reference point, and the red dashed line represents the F_{max}.

Discussion

The results derived from both length-based approaches confirm that kingclip is being caught at too small sizes. The smallest sizes are being caught in commercial fishery, followed by July and February surveys. Differences in selectivity-at-length were also detected between February and July survey information, with the length at 50% selectivity bigger in February survey. Given that both surveys use the same cod-end mesh size, those differences could be more related to the biology of the kingclip, which migrates to reproductive areas during summer (Sammarone, 2019). As the bigger fish have better swimming capabilities than the smaller fish (Rubio-García *et al.*, 2020), this could cause bigger fish to arrive at the feeding grounds in FI waters earlier, and be predominant in the month of February, while the smaller fish are still arriving. By July, the whole size range in FI waters has arrived, leading to a higher catch of smaller fish, and thus lowering the estimated selectivity lengths.

The LBB approach showed a relative biomass (B/B_0) below the estimated proxy for B_{MSY} for all models and all datasets. In the most optimistic scenarios (LBB1) the relative biomass was close to (February and commercial fishery data) or above (July data) the limit reference point (0.5 of the estimated proxy for B_{MSY}). The model LBB1 used the default uninformative priors. However, when including prior information, the results show a relative biomass close to or below the limit reference point proxy. If following the recommended approach and using stock-specific priors (Froese *et al.*, 2018), the results demonstrate there should be concern about the status of the kingclip stock. In all the models and for all datasets the median catch length was estimated below the optimal catch length.

Froese (2004) proposed three simple indicators to detect overfishing. The percentage of mature fish in catch should be 100%, the percent of specimens caught at optimum length should also be 100%, and the percent of mega-spawners target should be 0%. Mega-spawners refer to the largest and oldest individuals in a fish population, which are considered to contribute disproportionately to reproductive output due to their higher fecundity. These individuals are vital for the sustainability of fish stocks, as they produce a significant number of eggs, enhancing the resilience and recovery potential of the population. In comparison, in the Falkland Islands commercial kingclip fishery, only 39% of the caught individuals were classified as mature. The estimated median catch length for 2024 ranged from 0.62 to 0.73 of the optimal catch length between the models. Although the LBB model does not explicitly estimate the proportion of mega-spawners, an indirect proxy is provided through the ratio of the length corresponding to the 95th percentile of the catch (L_{95th}) to the asymptotic length (L_{inf}). This ratio (L_{95th}/L_{inf}) indicates how close the largest individuals in the catch are to the theoretical maximum length, and can be used as an approximate indicator of the presence of mega-spawners in the exploited stock. The range for this parameter was from 0.91 to 0.99 across the models, confirming the existence of the so-called 'mega-spawners' in the catch composition (values above 0.9 are considered to be a threshold proportion of large spawners). The catch of a large number of juvenile individuals could have long term effects in the stock with a reduction in the future yield and subsequent recruitment to the fishery (Crowder & Murawski, 1998; Najmudeen & Sathiadhas, 2008). As kingclip is a top predator, this could also lead to cascade effects, with unknown effects for the whole community (Heithaus *et al.*, 2008). On the other hand, letting fish spawn at least once could improve recruitment and avoid stock collapse (Myers & Mertz, 1998). Moreover, the larger the difference between age (or length) at first capture and age (or length) at first maturity, the more vulnerable the stock will be to overfishing (Myers & Mertz, 1998).

The LBSPR approach showed similar results to the LBB approach, with the estimated spawning potential ratio (SPR) being below 0.2 for all models and with all datasets, when the expected spawning potential ratio reference point is 0.4 and its limit 0.2 (Hordyk *et al.*, 2015a). In the same sense, the selectivity pattern showed fish being caught before their maturity, and the expected size composition for a healthy stock being different to the sample size composition. These results again raise concerns about the status of the stock and the size of fish caught. With these results in mind (stock close or below the limit reference points), actions may be needed in order to recover the health of the stock.

The yield per recruit method showed, in the same sense as the other methods, that fish are being caught at too small sizes. The fishing exploitation rate at which the spawning biomass per recruit is 40% of the unfished spawning biomass per recruit ($F_{40\%}$) for the commercial fishery was estimated at 0.109 and F_{max} at 0.24. The shape of the YPR curve indicates that, given the estimated selectivity-at-length of the commercial fishery, few individuals will be able to reach maturity, which could compromise future recruitment. This could have long-term effects on the population. The yield per recruit analysis provides insight into the dynamics of the stock in terms of their response to changes in fishing mortality, particularly with regard to the size-at-first-capture of the fishery (Liang & Pauly, 2016). Although this kind of analysis does not explicitly consider uncertainty (Beverton & Holt, 1957), the outcome was consistent with the length-based methods. A length at 50% selectivity closer to 80 cm would give a better theoretical yield per recruit while allowing the population to reach 40% of the population maximum spawning potential (e.g. egg production), which would be obtained without any fishing. It should be noted that YPR analyses are only correct in the long-term context. In the short term, increasing the fishing mortality beyond F_{max} or reducing the size at first capture may result in an immediate increase in the total catch. However, in the long term, these harvesting strategies may result in a decrease in potential yield.

Although the results from the stock assessment of the kingclip in Falkland Islands waters showed contradictory results, with the biomass being estimated below or above the reference points (0.5 of the unfished total biomass) depending on the relative abundance index employed in the model (García, 2024), the results from both length-based models from this report were in concordance with the stock assessment done for the whole kingclip stock, which showed biomass levels below the limit reference point (20% of the unfished spawning biomass; Di Marco, 2022). Despite the Argentine government imposing restrictions on kingclip fishing, no evidence of a biomass recovery has been detected (Di Marco, 2022). This is also consistent with recent results of the February 2025 groundfish survey, which estimated the CPUE of kingclip in Falkland Islands waters to be the lowest since 2010 (Ramos *et al.*, 2025). It is also in line with the biomass estimated from the February 2025 parallel demersal surveys (groundfish and calamari pre-season surveys), which was found to be the lowest since the first such surveys in February 2010, at 47% of the 2010 biomass level (Ramos, 2025). If the fish are being caught before they have reached sexual maturity, it is difficult for the stock to recover. In this sense, special concern should be given to the fact that the commercial fishery is catching kingclip at sizes below their length at first maturity.

Final considerations

This report highlights the fact that the kingclip is being caught at small sizes. This could have effects not only on the stock, but also on the community given its role as top predator. It is recommended to develop management measures in order to protect the population.

A straightforward measure for kingclip conservation would be to treat it as by-catch species instead of permitted species, and enforcing the 10% by-catch move-on rule. This measure should be imposed as soon as possible, given the critical condition of the stock.

Other protection measures are also recommended for kingclip due to its vulnerability. For example, the identification of the areas with high aggregations of the species should be of primary interest. After this step is completed, a second step should include restrictions for the trawling inside those areas. Regulating minimum size-at-landing to be above kingclip size at maturity should also be considered. This measure should include catch controls by observers and occasional checks by FishOps.

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Appendix

Table A1. Estimates of the different LBSPR models to the February surveys data. SL50: length at 50% selectivity; SL95: length at 95% selectivity; FM ratio between fishing and natural mortality; SPR: spawning potential ratio.

Model	Year	SL50	SL95	FM	SPR
LBSPR1	2010	53.40	64.13	3.27	0.09
	2019	53.84	64.70	3.40	0.09
	2020	55.32	66.86	3.68	0.09
	2021	57.79	70.57	4.09	0.09
	2022	60.39	74.47	4.51	0.09
	2023	62.13	76.93	4.68	0.09
	2024	63.15	78.31	4.77	0.09
LBSPR2	2010	53.5	64.1	2.45	0.14
	2019	53.93	64.67	2.56	0.13
	2020	55.41	66.81	2.78	0.13
	2021	57.89	70.50	3.12	0.12
	2022	60.50	74.36	3.45	0.13
	2023	62.25	76.81	3.59	0.13
	2024	63.27	78.19	3.67	0.13
LBSPR3	2010	53.12	63.64	2.46	0.14
	2019	53.56	64.23	2.56	0.13
	2020	55.04	66.38	2.78	0.13
	2021	57.49	70.08	3.1	0.13
	2022	60.07	73.96	3.41	0.13
	2023	61.8	76.39	3.53	0.13
	2024	62.81	77.76	3.59	0.14

Table A2. Estimates of the different LBSPR models to the July surveys data. SL50: selectivity length at 50%; SL95: length at 95% selectivity; FM ratio between fishing and natural mortality; SPR: spawning potential ratio.

Model	Year	SL50	SL95	FM	SPR
LBSPR1	2020	59.43	73.74	3.99	0.09
	2022	60.29	75.08	3.98	0.09
	2023	61.75	77.02	4.07	0.1
	2024	61.82	77.03	4	0.1
LBSPR2	2020	59.55	73.66	3.03	0.12
	2022	60.42	74.99	3.03	0.13
	2023	61.88	76.92	3.1	0.13
	2024	61.95	76.93	3.04	0.14
LBSPR3	2020	58.95	72.94	2.99	0.12
	2022	59.79	74.22	2.97	0.13
	2023	61.25	76.18	3.03	0.14
	2024	61.33	76.2	2.97	0.14

Table A3. Estimates of the different LBSPR models to the commercial fishery data. SL50: selectivity length at 50%; SL95: length at 95% selectivity; FM ratio between fishing and natural mortality; SPR: spawning potential ratio.

Model	Year	SL50	SL95	FM	SPR
LBSPR1	2004	54.25	65.32	2.76	0.16
	2005	55.06	66.6	2.95	0.15
	2006	56.28	68.59	3.06	0.15
	2007	57.69	71	3.29	0.14
	2008	57.94	71.76	3.48	0.14
	2009	54.9	67.65	3.09	0.14
	2010	52.79	64.79	2.91	0.13
	2011	51.33	62.91	2.77	0.12
	2012	49.92	61.09	2.68	0.11
	2013	49.03	60	2.67	0.11
	2014	48.35	59.22	2.72	0.1
	2015	47.84	58.65	2.89	0.09
	2016	47.09	57.85	3.1	0.09
	2017	46.48	57.06	3.34	0.08
	2018	46.45	56.82	3.78	0.07
	2019	47.28	57.8	4.24	0.06
	2020	48.92	60.03	4.56	0.05
	2021	50.69	62.48	4.75	0.05
	2022	51.96	64.41	4.65	0.05
	2023	52.58	65.53	4.53	0.05
	2024	52.69	65.67	4.41	0.05
LBSPR2	2004	54.32	65.23	2.03	0.23
	2005	55.13	66.5	2.18	0.22
	2006	56.34	68.46	2.26	0.21
	2007	57.74	70.83	2.45	0.21
	2008	57.97	71.54	2.6	0.21
	2009	54.96	67.5	2.29	0.21
	2010	52.86	64.68	2.15	0.19
	2011	51.4	62.84	2.04	0.18
	2012	49.99	61.03	1.97	0.17
	2013	49.11	59.96	1.96	0.16
	2014	48.44	59.18	2	0.15
	2015	47.92	58.62	2.14	0.14
	2016	47.17	57.82	2.31	0.13
	2017	46.56	57.04	2.51	0.12
	2018	46.53	56.8	2.87	0.10
	2019	47.36	57.78	3.24	0.08
	2020	49.01	60	3.49	0.08
	2021	50.78	62.45	3.65	0.07
	2022	52.06	64.37	3.57	0.08
	2023	52.68	65.48	3.47	0.08
	2024	52.8	65.62	3.37	0.08

Table A3. (Cont.)

Model	Year	SL50	SL95	FM	SPR
LBSPR3	2004	54.25	65.32	2.76	0.16
	2005	55.06	66.6	2.95	0.15
	2006	56.28	68.59	3.06	0.15
	2007	57.69	71	3.29	0.14
	2008	57.94	71.76	3.48	0.14
	2009	54.9	67.65	3.09	0.14
	2010	52.79	64.79	2.91	0.13
	2011	51.33	62.91	2.77	0.12
	2012	49.92	61.09	2.68	0.11
	2013	49.03	60	2.67	0.11
	2014	48.35	59.22	2.72	0.1
	2015	47.84	58.65	2.89	0.09
	2016	47.09	57.85	3.1	0.09
	2017	46.48	57.06	3.34	0.08
	2018	46.45	56.82	3.78	0.07
	2019	47.28	57.8	4.24	0.06
	2020	48.92	60.03	4.56	0.05
	2021	50.69	62.48	4.75	0.05
	2022	51.96	64.41	4.65	0.05
	2023	52.58	65.53	4.53	0.05
	2024	52.69	65.67	4.41	0.05

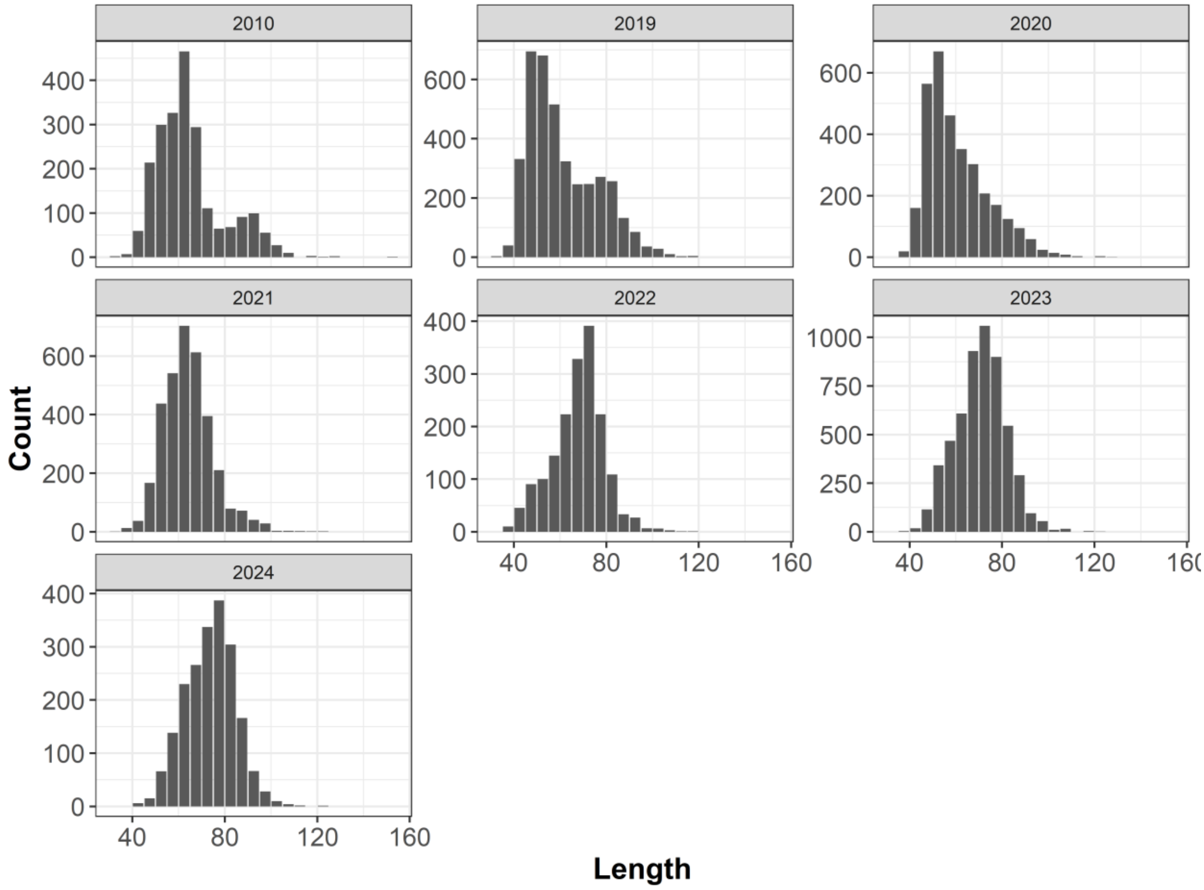

Figure A1. Length-frequency histogram of the expanded sample from the February groundfish surveys.

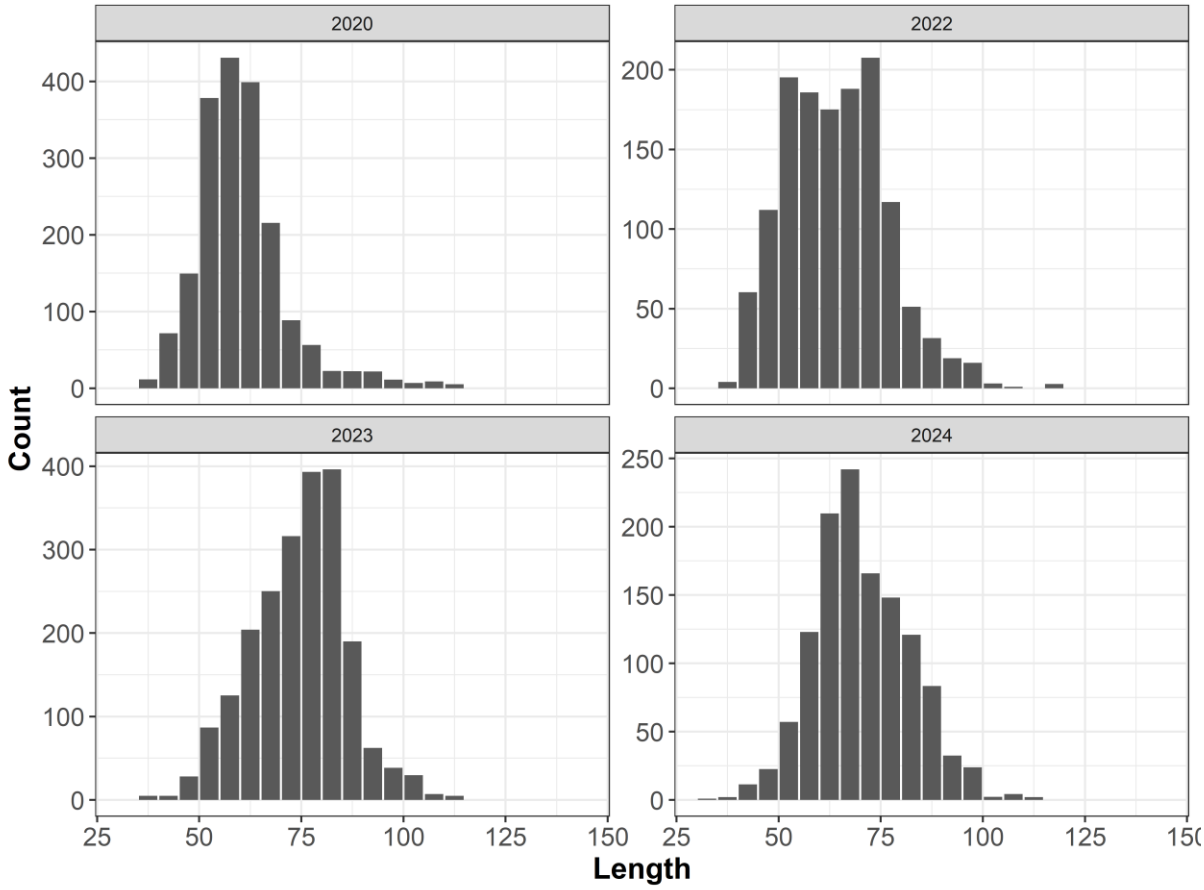

Figure A2. Length-frequency histogram of the expanded sample from the July groundfish surveys.

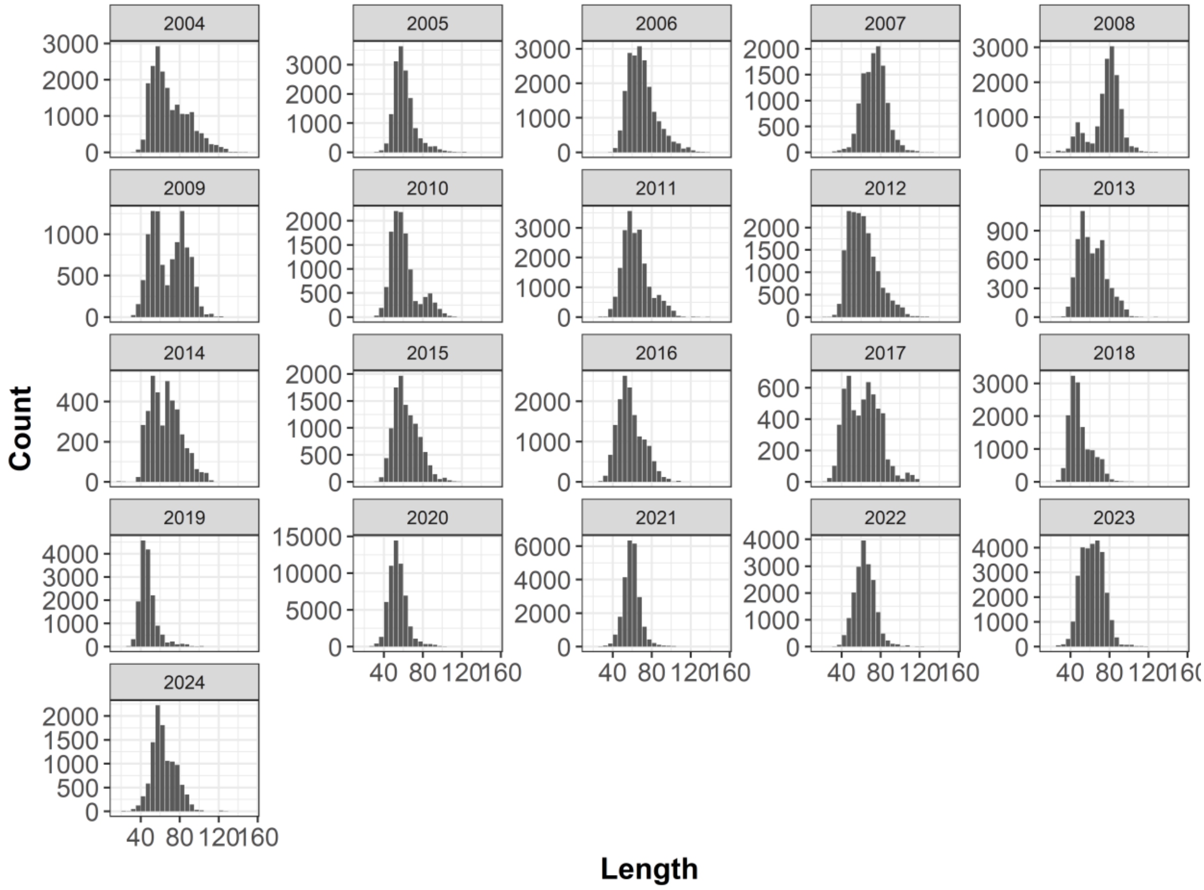

Figure A3. Length-frequency histogram of the expanded sample from the commercial fishery samples.

Stepwise Algorithms for LBB and LBSPR

Length-Based Bayesian Biomass (LBB) Model

Input Data:

- Length-frequency data representative of the exploited population.

1. Data Preparation:

- Group observed lengths into appropriate size classes (e.g., 5 cm intervals).

2. Model Assumptions:

- Growth follows the von Bertalanffy Growth Function (VBGF):

$(L(t) = L_\infty\left(1 - e^{-K(t-t_0)}\right))$

Where:

L(t)L(t)L(t): length at age ttt

$L\infty$: asymptotic length

K: growth coefficient

t_0: theoretical age at length zero

- Natural mortality (M) is constant across sizes.

- Fishing mortality (F) is size-selective, beginning at the length of first capture (L_c).

3. Parameter Estimation:

- Estimate parameters: (L_∞), (M/K), (L_c), and (F/M).

4. Expected Length Distribution:

$$N(l) \propto \frac{1}{K(L_\infty - l)}\left(1 - \frac{l}{L_\infty}\right)^{Z/K}$$

$N(l)$: number of individuals at length l

$Z = M + F(l) \cdot S(l)$: total mortality at length l

5. Selectivity Function (logistic):

$$S(l) = \frac{1}{1+e^{-s_1(l-L_{50})}}$$

Where:

S(l): selectivity at length l

L_{50}: length at 50% selectivity

s_1: steepness of the curve

6. Likelihood Function:

- Use a multinomial or log-likelihood function to compare observed and expected length distributions.

7. Bayesian Estimation:

- Apply MCMC (via JAGS) with appropriate priors to estimate posterior distributions.

8. Convergence and Outputs:

- Derive posterior medians and 95% credible intervals for parameters.

- Calculate relative biomass indicators:

Biomass relative to unexploited biomass:

$$\frac{B}{B_0} = \frac{SPR}{SPR_0}$$

Biomass relative to MSY:

$$\frac{B}{B_{MSY}} = \frac{B/B_0}{B_{MSY}/B_0} \approx \frac{SPR}{SPR_0} 0.4$$

Where:

SPR: spawning potential ratio under fishing

SPR_0: spawning potential ratio in unfished state

B_0: unfished biomass

B_{MSY}: biomass producing MSY

Assumes $B_{MSY}/B_0 \approx 0.4$ for many life histories

Length-Based Spawning Potential Ratio (LBSPR) Model

Input Data:

- Length-frequency data
- Life-history parameters: (L_∞), (K), (M/K), (L_{50}), (L_{95})

1. Model Assumptions:

- Growth follows VBGF.

- Maturity and selectivity follow logistic functions:

$$S(l) = \frac{1}{1+e^{-s_1(l-L_{50})}}$$

$$M(l) = \frac{1}{1+e^{-m_1(l-L_{m50})}}$$

Where:

S(l): selectivity at length l

M(l): maturity at length l

L_{50}, L_{95}: maturity lengths

2. Spawning Output by Length:

$$SO(l) = N(l) \cdot M(l) \cdot w(l)$$

Where:

$N(l)$: equilibrium number at length

$M(l)$: proportion mature

$w(l)$: weight at length (usually $a \cdot l^b$)

3. Equilibrium Length Distribution:

$$N(l) \propto \frac{1}{K(L_\infty - l)} \left(1 - \frac{l}{L_\infty}\right)^{Z/K}$$

with $Z = M + F(l) \cdot S(l)$

4. Model Fitting:

- Use multinomial likelihood to compare observed and predicted length distributions.

5. Optimization:

- Estimate (F/M) or the spawning potential ratio (*SPR*).

6. Outputs:

- Spawning potential ratio (SPR):

$$SPR = \frac{\sum[N(l) \cdot M(l) \cdot w(l)]}{\sum[N_0(l) \cdot M(l) \cdot w(l)]}$$

Where $(N_0(l))$ is the unfished equilibrium abundance.

SPR is compared to biological reference points:

$$SPR_{target} = 0.4$$

$$SPR_{limit} = 0.2$$

Compare SPR to thresholds (0.4 for target, 0.2 for limit) to assess stock status.

"States and subregional and regional fisheries management organizations should apply a precautionary approach widely to conservation, management and exploitation of living aquatic resources in order to protect them and preserve the aquatic environment, taking account of the best scientific evidence available. The absence of adequate scientific information should not be used as a reason for postponing or failing to take measures to conserve target species, associated or dependent species and non-target species and their environment."

FAO, 1995. Code of conduct for Responsible Fisheries. Article 6.5