Indian Ocean Tuna Commission
Commission des Thons de l'Ocean Indien

Stock assessment blue shark (*Prionace glauca)* in the Indian Ocean using Stock Synthesis.

Joel Rice[1]

IOTC Secretariat
PO Box 1011
Victoria, Seychelles

[1] Joel Rice Consulting Ltd. (joelrice@uw.edu)

Executive summary
This paper presents the second stock assessment of blue shark in the Indian Ocean. The assessment uses the stock assessment model and computer software known as Stock Synthesis (version 3.24f http://nft.nefsc.noaa.gov/Download.html). The blue shark assessment model is an age structured (30 years), spatially aggregated (1 region) and two sex model. The catch, effort, and size composition of catch, are grouped into 8 fisheries covering the time period from 1950 through 2015. Seven indices of abundance, all from longline fisheries, were available as well as three estimates of total catch. The estimates of catch are the reported nominal catch, catch estimates based on a generalized additive model and based ratio estimates, the later being available only from 1971 on. The data collected previous to 1971 were not considered in the previous assessment (WPEB11-28), however are included in in this of the analysis however are considered here for the two catch series extending to 1950.

Blue sharks are most often caught as bycatch in the Indian Ocean tuna fisheries, though some directed mixed species (sharks and tunas/billfish) fisheries do exist. Commercial reporting of landings has been minimal, as has information regarding the targeting and fate of blue sharks encountered in the fisheries. Useful data on catch and effort is mostly limited to recent years, a time series of historical catch has been estimated based on reported effort and observed catch rates.

This analysis was developed as an assessment model that included all seven of the submitted CPUE series, and the nominal catch series, this model named the reference case, as it is referred to in the when presenting the model parametrization and diagnostics. A grid of sensitivity runs using the individual CPUE series and the three catch estimates is used to characterize the major axes of uncertainty. These models vary in their inputs and as such the estimated stock status differs between combinations of the catch datasets and CPUE series. The Indian Ocean Tuna Commission Working Party on Ecosystems and Bycatch is invited to recommend a base case model, for the provision of stock status.

Estimates of stock status from the reference case and sensitivity runs are are $SB_{CURRENT}/SB_{MSY}$ = 1.07-2.06 and $F_{CURRENT}/F_{MSY}$= 0.35-1.78. Stock status is reported in relation to MSY based reference points however please take note that the IOTC has not yet adopted reference points for sharks. Due to the inherent unreliability of recruitment estimates in the terminal year this study defines 'current' as the average of the first four of the last five years (i.e. 2011-2014).

The main conclusions of this assessment are:
1. The stock status is highly dependent on the CPUE series used to fit the model. Among the candidate CPUE models in this assessment no CPUE series runs the through the entire time series.
2. The estimates of catch are highly influential in the model, but mostly in terms of scale, as the current depletion and fishing mortality indicators are approximately equal across all catch estimates for a given CPUE series.

3. The scale of the assessment is influenced by the CPUE series chosen and by the catch estimates used, estimates of B0 range from approximately 700,000 metric tons to over 3 million metric tons.

When considering which model(s) to use for the provision of management advice, it is recommend that advice be based upon multiple model runs that consider the major axes of uncertainty.

1 Introduction

Blue shark (*Prionace glauca*) are a large pelagic species, broadly distributed throughout the Indian Ocean to a southern limit of ~50° S (Figure 1). Indian Ocean blue shark have been incidentally caught by the Japanese longline fleet since the early 1950s. The population was not heavily exploited before targeted fisheries (or bycatch rates increased) in the early 1990s. At this time the Taiwanese long line vessels began taking large numbers, initially in the SW region, followed by the other areas (Figure 1). The European longline fleet (predominantly Spanish vessels) started a targeted fishery in the 1990s, while only small numbers are reported in the driftnet fisheries, and purse seine catches are very rare.

2 Methods

Data

There are many different fleets catching blue shark in the Indian Ocean, with vastly different gear types and levels of data quality (Martin et. al. 2015). This model uses the same fleet and survey structure, 8 fleets, and 4 surveys, as previously used (IOTC–WPEB10 2014, WPEB11-28) There is enough uncertainty about the selectivity assumptions with respect to time, and the low numbers of size composition data, that we would not expect the size composition data to be very informative about year-class strength. Hence, in most model runs presented here, we down weighted the length-composition data so as to let it inform the selectivity but not alter the model fit to the abundance trend.

Total catch

Catch estimates by year and fishery are shown in Figure 2. In the previous assessment (Rice and Sharma 2015), it was assumed that the catch in mass figures provided by the IOTC members and cooperating non-contracting parties (CPC's) were the most reliable catch data available. This assumption has been re-examined an additional estimates of total catch were produced based on generalized linear models (GAM) and the ratio of blue shark (BSH) to total target catch (Martin et al 2017 and Coelho 2017). While the total catch data are estimates, they are derived in large part from the industrial fleets in the Indian Ocean and are thought to be more reasonable for blue shark than for the other shark species.

The major concern identified with respect to the catch time series are that catch-and-effort for BSH are highly incomplete. Reliable data are tough to be available for a limited number of years (i.e., from the late-1990s onwards) and for an very limited number of fisheries. In the previous assessment an alternative catch series was used based on trade based estimates using the proportion of tuna caught (Clarke, 2011). This series extends from 1981-2011, and was previously extended using a ratio based approach. This method used the nominal to trade based estimates ratio from the years previous to 2011 to estimate the values for the following years. Because of the uncertainty in the reported nominal catches this method was not repeated for this analysis. The chief drawback of not using the trade based estimates is that the three other catch estimates are the result of using three separate methods on what is essentially the same data set, while method employed by Clarke (2014) uses a separate, though highly aggregated, dataset.

2.1 Relative abundance indices

The standardized CPUE series in 2017 were somewhat different from those previously submitted to the WPEB. Newly estimated CPUE series by Japan, Taiwan, Portugal, Spain, Indonesia and EU France (Reunion) were used in this analysis (Figure 2) All of these are based on bycatch in the longline fisheries..

2.2 Size composition data

As with the previous analysis sex based length-composition data collected by observers and from logsheets for the main fleets (Japan, Taiwan and Portugal) was used along with additional length composition data submitted to the IOTC in the last two years. In all, approximately twenty years of length composition data from the LL fleets was organized and used in the analysis. Some size and sex composition data of catch were available, but in many cases the data were in aggregated form covering several years, or size sampling was incomplete across fisheries. Many of the time series suffered from low sample sizes and inconsistencies across years. For this reason and because of the evidence that there was a conflict between the CPUE and the size data (see results below) lower weight was given to the size data in the model, this allowed the model to estimate selectivity, but not to overwhelm the model. We assumed an annual effective sample size calculated as the to the overall (male and female) sample size divided by 40. The annual sample size was then weighted by the Francis (2011 and 2014) likelihood weighting method.

2.3 Software

The analysis was undertaken with Stock synthesis SS V3.234F, 64 bit version (Methot 2000, 2009, executable available from http://nft.nefsc.noaa.gov/SS3.html), running on MS Windows^{TM} 10. Typical function minimization of the fully disaggregated model on a 3.0 GHz personal computer required about 10 minutes. Additional simplifications and aggregations could probably reduce the minimization time further, without significant loss to the stock status inferences. However, given the current exploratory manner in which the model is being used to describe interactions among assumptions, the disaggregation is considered to be useful and the computation speed does not represent a real problem.

2.4 General assessment approach

As with previous shark assessments undertaken by other RFMO's the general approach was to identify the key areas that contributed greatest to the uncertainty regarding stock status and then explore the implication of different assumptions on each. In doing this we first identify a 'reference case' model, which is not necessarily the 'best' or 'base case' model but rather a model that we think is reasonable, and use this to present the range of key model diagnostics. Next we identify a range of areas or axes of uncertainty and choose some options for each. For example we consider the steepness of the stock recruitment relationship to be an area of uncertainty and consider three options under it. We then run the set of models that reflect a single change from the reference case and these are our one-change sensitivities. Finally we run a full grid with all the options across all the axes of uncertainty. This is useful to determine if there are particular interactions between model assumptions / data inputs.

2.5 Model Assumptions

The most important model assumptions are described in the following sections. Standard population dynamics and statistical terms are described verbally, while equations can be found in Methot (2000, 2009). Attachment 1 is the template specification file for all of the models, and includes additional information on secondary elements of model formulation which may be omitted in the description below. All of the specification files are archived with the IOTC Secretariat.

Table 2 lists the assumption options that were combined in a balanced 'grid' design (i.e. all possible combinations of the listed assumption options were fit, while the other assumptions remained constant).

2.6 Time Period

The model was iterated from 1950-2015 using an annual time-step, however, further analysis of seasonal processes is encouraged. For a subset of the runs considered the timeframe was shorted to 1971-2015 due to the contracted time series of catches.

2.7 Biological inputs and assumptions

Blue sharks have a Indian Ocean wide distribution, and genetic evidence of distinct population structure within other oceans (e.g. Pacific) has not been found (Taguchi and Yokawa 2013), and hence assumed homogenous here as well. Conventional tagging studies need to be examined in the Indian Ocean, but currently limited data exist, though some tagging effort in the Pacific shows limited movement to the western Australian EEZ. In addition to assumptions regarding stock structure, the other critical information on the biology of blue shark necessary for the SS assessment relates to sex-specific growth, natural mortality, maturity and fecundity.

2.8 Growth

The standard assumptions made concerning age and growth in the SS model are (i) the lengths-at-age are assumed to be normally distributed for each age-class; (ii) the mean lengths-at-age are assumed to follow a von Bertalanffy growth curve. For any specific model, it is necessary to assume the number of significant age-classes in the exploited population, with the last age-class being defined as a "plus group", i.e. all fish of the designated age and older. For the results presented here, 30 yearly age-classes have been assumed, as age 30 approximates to the age at the theoretical maximum length of an average fish.

No attempt was made to estimate growth within the model due to the uninformative nature of the size data to track cohorts through time. The previous assessment considered the growth curves from Hsu et al. (2011) as well as specific formulations based on data from the Indian

Ocean. This assessment uses a new sex specific growth curves developed by based on data from the Indian Ocean (Andrade et al 2017). A CV of 0.25 was used to model variation in length-at-age. All lengths reported from the assessment relate to fork length (FL).

2.9 Natural mortality

Sets of age and sex-specific natural mortality ogives were considered in the assessment calculated based on the Peterson and Wroblewski (1984) method (Rice and Semba 2014) (Table 3).

2.10 Maturity and fecundity

For the purpose of computing the spawning biomass, we assume a logistic maturity schedule based on length with the age-at-50% maturity for females equal to 145cm (Nakano and Seki 2003). There is no information which indicates that sex ratio differs from parity throughout the lifecycle of blue shark. Fecundity was fixed to an average of 25 pups per annual gestation period.

2.11 Population and fishery dynamics

The model partitions the population into 30 yearly age-classes in one region (Figure 1). The last age-class comprises a “plus group” in which mortality and other characteristics are assumed to be constant. The population is “monitored” in the model at yearly time steps, extending through a time window of 1950-2015. The main population dynamics processes are as follows: In this model “recruitment” is the appearance of age-class 1 fish (i.e. fish averaging approximately 50 cm in the population). The results presented in this report were derived using one recruitment episode per year, which is assumed to occur at the start of each year. Annual recruitment deviates from the recruitment relationship were estimated, but constrained reflecting the limited scope for compensation given estimates of fecundity. Deviations from the SRR were estimated in two parts; one the early recruitment deviates for the 5 years prior to the model period before the bulk of the length composition information (1966 -1970) and two being the main recruitment deviates that covered the model period (1971 - 2015).
There is no information which indicates that sex ratio differs from parity throughout the lifecycle of blue shark. In this assessment the term spawning biomass (SB) is a relative measure of spawning potential (the mature female population) and is a unit less term of reference. It is comparable to other iterations of itself, but not to total biomass.

2.12 Initial population state

In the previous model it was assumed that the blue shark population was at an unfished state of equilibrium at the start of the model (1950) as longline fishing occurred in the region for a significant number of years (at least from the 1950s onwards). For the scenarios in the sensitivity analysis that included catch estimaes from 1971 on the model was parameterized to estimate an initial equilibrium fishing mortality, which would result in a stable age distribution, impacted by fishing, which would match the observed age distribution at the start of the time series. In this case the initial catch was set to approximately 50% of the first five year the estiamed catch of the model to represent a plausible estimate for the initial depletion.

The population age structure and overall size in the first year is determined as a function of the estimate of the first years recruitment (R_1) offset from virgin recruitment (R_0), the initial 'equilibrium' fishing mortality discussed above, and the initial recruitment deviations. As the size data were found to be uninformative about initial depletion and recruitment variation only a small number (five) of initial recruitment deviates were estimated.

2.13 Selectivity Curves

Selectivity is fishery-specific and was assumed to be time-invariant. A double-half normal functional form was assumed for all selectivity curves except the miscellaneous fishery which was set to a logistic. An offset on the peak and scale was estimated for sex-specific differences in selectivity that were evident in the data. The selectivity function location and scale were estimated for fleets 3, 4, 6,7 and 8 and with the ascending and descending functions were fixed to a best fit when estimated independently, only the location parameter was estimated for fleet 5 as the model failed to converge if the scale was also estimated.

2.14 Parameter estimation and uncertainty

Model parameters were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors, and the normalized sum of the recruitment deviates estimated in the model. For the catch and the CPUE series we assumed lognormal likelihood functions while a multinomial was assumed for the size data. The maximization was performed by an efficient optimization using exact numerical derivatives with respect to the model parameters (Fournier et al. 2012). Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix. This was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

3 Results

In this section we focus on the results from the reference case model and the key results and diagnostics for this model. We then comment on any important differences in both outputs and model diagnostics for the sensitivity analyses, and present all results.

3.1 Reference case model

The reference case model choice is described in section 2.15. The choice of model parameters and data inputs reflected the sum total of all the data.

<u>Estimated parameters and model performance</u>

We found differences in the sex-specific selectivity curves for many of the fisheries which reinforce the observations of biologists for areas of sex-segregation during the life history of blue sharks (Figure 6). With the exception of the Japanese longline fishery; all fisheries where sex specific selectivity could be estimated resulted in a lower peak selectivity (therefore catchability) for females.

The overall fit to the length data was generally good (Figures 7,8). Fleet specific annual length samples were often quite different, i.e. left skewed one year and bimodal the next, which

accounts for the small amount of misfit in the aggregated samples. When attempting to estimate selectivity curves for fisheries with sex specific patterns the model often did not converge, therefore the sex specific offsets were fixed. Pearson residuals of the fit to the length compositions were small – on the order of 2 to -2 and did not show any temporal trend (Figures 9, 9a).
The fit to the CPUE indices was generally good for the reference case model (Figure 10). The fit to the CPUE series was good for the JPN early series, the ESP series and the Reunion CPUE series but a bad fit for the Taiwanese, Indonesian and Japanese Late series. The reference case model fit the middle part of the Portuguese series well, under fit the early part and overfit the latter part of the series while staying within the confidence intervals for all years.

As part of an analysis of model structure retrospective analysis (sequentially deleting 1 year of data from the end of the model and re-running) was run using the Portuguese, Japanese late and Spanish CPUE series and the IOTC database catches. Due to late revision the Taiwanese CPUE series was not used for a retrospective analysis. While the retrospective analysis showed some change in scale for the for the estimates of spawning biomass, especially with the deletion of 3 or more years of data, there was no systematic bias in the direction of the change across the three CPUE series analysed (Figure 18). The estimates of spawning depletion remain very similar across all the retrospective model runs considered indicating that the changes in estimates of spawning biomass are based on the total catch (Figure 18 right hand column).

<u>Estimated stock status and other quantities</u>
The reference case model estimates that the total biomass of the stock was at approximately 100% of the unfished level at the start of the model period (Table 4 and Figure 11) and steadily decreased to an estimate of $SB_{CURRENT}/S_{B0}$ =63%-92% based on the IOTC nominal catches, $SB_{CURRENT}/S_{B0=}$ 57%-88% for the GAM based catches, and $SB_{CURRENT}/S_{B0=}$ 51%-81% for the ratio based estimaes. Recruitment is fairly well estimated throughout the model time period (Figures 12 and 13), with recent recruitment estimated to be lower than then implied stock recruitment curve due to deviations implied by the length data. The estimates of recruitment were quite tightly constrained to the stock recruitment curve for the initial period of the model when there was no length information to inform the model. The main trends in the population dynamics can be explained through the estimated fishing mortality which was greatly increased in the 1990's and early 2000's due to the increase in catch (Figure 14).

SS provides estimates of the MSY-related quantities and these and other quantities of interest for management are provided in Table 4. We note that the IOTC has not yet adopted target or limit reference points for any shark species, so a broad suite of MSY-related quantities are presented.

In the reference case the estimated MSY is approximately 33000 MT and this is predicted to occur at 43% of the unfished biomass (Figure 15), which is similar to the standard Schaefer production model (0.5). Current catches are estimated to be in excess of MSY for all models except for the reference case model (IOTC Nominal catch and all CPUE series) and the ratio based catches and the JPN Early and Late CPUE Series. (C2015_MSY in Table 4).

The stock is declining due to an increase in F, F in the final year is greater than F_{MSY}, with estimates of $F_{CURRENT}/F_{MSY}$ ranging from 0.38 to 1.96 depending on the CPUE and catch series selected. Based on recent conditions (current) the spawning stock biomass is estimated to be $SB_{CURRENT}/S_{MSY}$ = 114%-207% depending on the CPUE and catch series. By the standard terminology, this would indicate that the stock may be experiencing overfishing but is not overfished.

4 Conclusion

Results for the assessment are compared across different assumptions with reference case parameterization resulting in estimates of $SB_{current}/SB_{MSY}$ =1.08% and $F_{current}/F_{MSY}$ =4.6 though the range of uncertainty is extensive. Stock status is reported in relation to MSY based reference points however the authors note that the IOTC has not yet adopted reference points for sharks. Due to the inherent unreliability of recruitment estimates in the terminal year this study defines 'current' as the average of the first four of the last five years (i.e. 2011-2014).

The main conclusions of this assessment are:

- The stock status is highly dependent on the CPUE series used to fit the model. Among the candidate CPUE models in this assessment no CPUE series runs the through the entire time series.
- The estimates of catch are highly influential in the model, but mostly in terms of scale, as the current depletion and fishing mortality indicators are approximately equal across all catch estimates for a given CPUE series.
- The scale of the assessment is influenced by the CPUE series chosen and by the catch estimates used, estimates of B0 range from approximately 700,000 metric tons to over 3 million metric tons.
- The stock status implied by the estimates of and $F_{current}/F_{MSY}$ across the grid showed multiple scenarios in which $F_{current}/F_{MSY}$ >1.

When considering which model(s) to use for the provision of management advice, it is recommend that advice be based upon multiple model runs that consider the major axes of uncertainty.

The main drivers of this assessment are the trend in the catch and CPUE series. In particular the large increase in recent years of catch has different interpretations – within the model- based on whether the CPUE series is slightly increasing (Japanese late) , decreasing (Portuguese), or relatively stable (Spanish).

Recommended work products that would improve future analysis are

- Develop appropriate length inputs for all fleet.
- Further investigation of CPUE series and their representativeness.
- Develop region specific biological inputs..
- Further work on developing catch histories.

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7 Tables

Table 1. Fishery definitions for the Indian Ocean Assessment

Fleet/ Survey Number and Short Name	Gear(s)	Selectivity
F1 MISC	Costal longline, trolling and artisanal fisheries	Fixed logistic
F2 GILL	Gillnet Fisheries	Fixed logistic
F3 OTHER_LL	All longline fishery other than Japan, TWN, China, Korea, Portugal and Spain.	Estimated double normal
F4 JPN_LL	Japanese longline fishery	Estimated double normal
F5 KOR_LL	Korean longline fishery	Estimated double normal
F6 PRT_LL	Taiwanese longline fishery	Estimated double normal
F7 TWN_LL	Portuguese longline fishery	Estimated double normal
F8 ESP_LL	Spanish longline fishery	Estimated double normal
S1 JPN_EARLY	Japan early years longline CPUE	NA
S2 JPN_LATE	Japan late years longline CPUE	NA
S3 POR	Portugal longline CPUE	NA
S4 ESP	Spain longline CPUE	NA
S5 TWN	Taiwanese longline CPUE	NA
S6 IND	Indonesian longline CPUE	NA
S7 REU	EU-Reunion longline CPUE	NA

Table 2: Estimates of age-specific natural mortality used in the assessment. The reference case used those based on the approach of Peterson and Wroblewski (1984) method and the Nakano data (Rice and Semba 2014).

	Natural Mortality	
Age	Male	Female
0	0.564	0.535
1	0.3	0.309
2	0.22	0.233
3	0.18	0.194
4	0.156	0.171
5	0.14	0.155
6	0.128	0.144
7	0.12	0.135
8	0.114	0.129
9	0.109	0.124
10	0.105	0.12
11	0.101	0.117
12	0.099	0.114
13	0.096	0.112
14	0.095	0.11
15	0.093	0.109
16	0.092	0.107
17	0.09	0.106
18	0.089	0.105
19	0.089	0.105
20	0.088	0.104
21	0.087	0.103
22	0.087	0.103
23	0.086	0.103
24	0.086	0.102
25	0.085	0.102
26	0.085	0.102
27	0.085	0.101
28	0.085	0.101
29	0.084	0.101
30	0.084	0.101

Table 2. Summary of SS3 specification options for the Indian Ocean blue shark assessment models. Other assumptions were constant for all models. The options below were applied in a balanced design (all possible combinations, such that a total 24 models were fit).

GROUP	Options Run
CPUE	
	1. All
	2. Japan Early and Late
	3. Japan Late
	4. Portugal
	5. Spain
	6. Taiwan
	7. Indonesia
	8. EU- Reunion
Catch series	1. **IOTC Nominal Catch**
	2. GAM based estimates
	3. Ratio based estimates

Table 4: Estimates of key management quantities for the reference case model and one change sensitivities.

Catch Series	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal
CPUE Series	JPNEarly&Late	PRT	JPN Late	ESP	TWN	IND	REU	ALL
C2015_msy	1.08	2.63	1.09	1.88	1.22	1.27	2.59	0.90
Y_MSY	27,649	11,386	27,563	15,940	24,486	23,513	11,550	33,170
B_zero	1,777,890	719,601	1,771,880	1,020,400	1,603,380	1,522,290	730,490	2,169,420
B_msy	772,051	312,975	769,460	443,320	695,373	660,663	317,692	941,019
B_cur	1,594,883	456,716	1,584,194	770,422	1,362,561	1,274,682	468,638	2,005,086
SB_zero	116,828	47,286	116,433	67,052	105,361	100,032	48,002	142,557
SB_msy	50,733	20,566	50,562	29,131	45,694	43,413	20,876	61,836
SB_cur	104,802	30,012	104,100	50,626	89,536	83,762	30,795	131,758
SB_cur/SB_zero	0.90	0.63	0.89	0.76	0.85	0.84	0.64	0.92
SB_cur/SB_msy	2.07	1.46	2.06	1.74	1.96	1.93	1.48	2.13
Fcur	0.05	0.18	0.05	0.10	0.06	0.06	0.17	0.04
F_msy	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
F_2015_msy	0.48	1.96	0.49	1.07	0.57	0.62	1.90	0.38
F_cur_msy	0.44	1.58	0.44	0.92	0.51	0.55	1.54	0.35

Catch Series	GAM	GAM	GAM	GAM	GAM	GAM	GAM	GAM
CPUE Series	JPNEarly&Late	PRT	JPN Late	ESP	TWN	IND	REU	ALL
C2015_msy	1.24	2.56	1.24	1.96	1.43	1.39	2.55	1.07
Y_MSY	44,039	21,355	43,967	27,883	38,387	39,322	21,436	50,951
B_zero	2,726,610	1,287,550	2,721,440	1,710,080	2,409,050	2,447,730	1,292,770	3,203,630
B_msy	1,191,501	563,872	1,189,271	747,957	1,051,796	1,069,145	566,150	1,398,516
B_cur	2,315,265	737,731	2,303,023	1,189,034	1,905,712	1,936,500	744,366	2,818,496
SB_zero	179,171	84,607	178,830	112,372	158,303	160,844	84,950	210,516
SB_msy	78,296	37,053	78,149	49,149	69,115	70,255	37,203	91,899
SB_cur	152,140	48,477	151,336	78,134	125,227	127,251	48,914	185,209
SB_cur/SB_zero	0.85	0.57	0.85	0.70	0.79	0.79	0.58	0.88
SB_cur/SB_msy	1.94	1.31	1.94	1.59	1.81	1.81	1.31	2.02
Fcur	0.06	0.21	0.06	0.13	0.08	0.08	0.21	0.05
F_msy	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
F_2015_msy	0.56	2.09	0.56	1.18	0.69	0.68	2.07	0.45
F_cur_msy	0.53	1.78	0.54	1.07	0.65	0.64	1.76	0.44

Catch Series	Ratio	Ratio	Ratio	Ratio	Ratio	Ratio	Ratio	Ratio
CPUE Series	JPNEarly&Late	PRT	JPN Late	ESP	TWN	IND	REU	ALL
C2015_msy	1.00	1.95	1.02	1.60	1.64	1.30	1.85	1.11
Y_MSY	66,770	34,359	65,685	41,880	41,019	51,772	36,231	60,263
B_zero	3,606,490	1,789,730	3,544,980	2,223,610	2,202,350	2,785,820	1,899,450	3,294,560
B_msy	1,605,800	797,782	1,578,469	990,797	980,750	1,240,653	846,596	1,466,239
B_cur	2,957,883	912,394	2,881,725	1,396,791	1,370,291	1,979,112	1,036,463	2,621,715
SB_zero	236,989	117,607	232,947	146,117	144,720	183,061	124,816	216,491
SB_msy	105,520	52,424	103,724	65,107	64,447	81,525	55,631	96,349
SB_cur	194,368	59,955	189,363	91,786	90,044	130,051	68,108	172,278
SB_cur/SB_zero	0.82	0.51	0.81	0.63	0.62	0.71	0.55	0.80
SB_cur/SB_msy	1.84	1.14	1.83	1.41	1.40	1.60	1.22	1.79
Fcur	0.05	0.20	0.05	0.12	0.12	0.08	0.17	0.06
F_msy	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
F_2015_msy	0.42	1.70	0.43	0.99	1.00	0.65	1.44	0.47
F_cur_msy	0.43	1.59	0.44	0.97	1.00	0.66	1.37	0.50

8 Figures

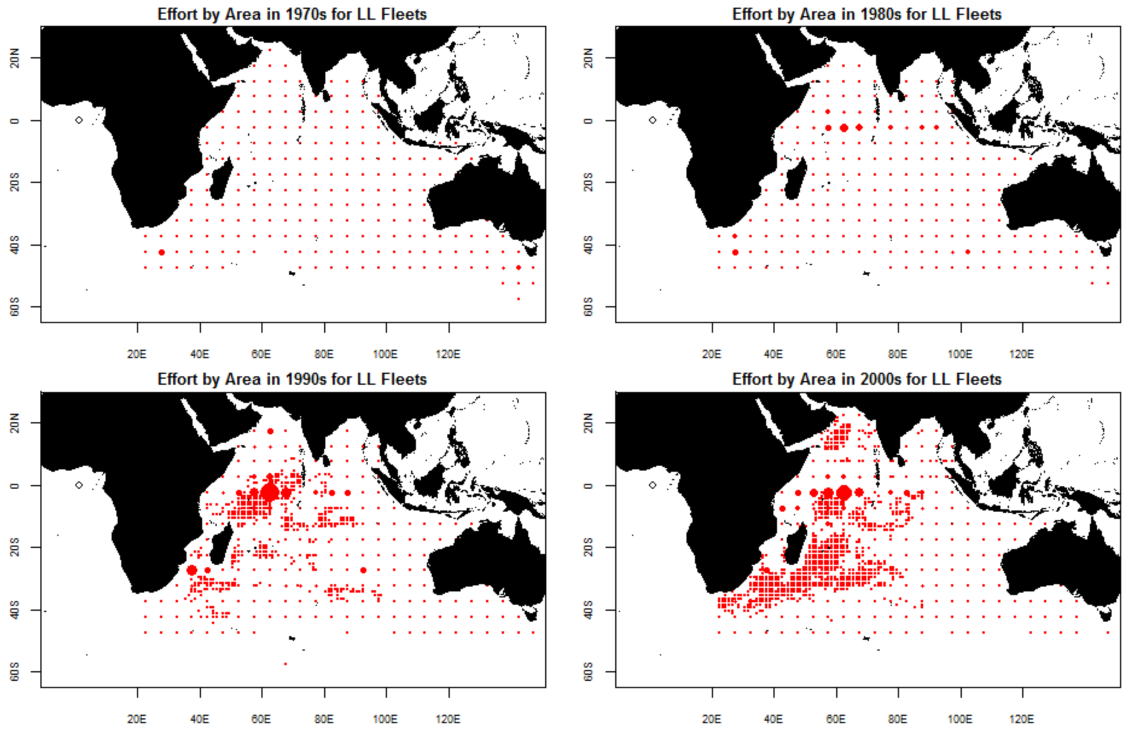

Figure 1. Study area and effort by decade. The red dots are proportional to the longline effort in each 5x5 degree cell.

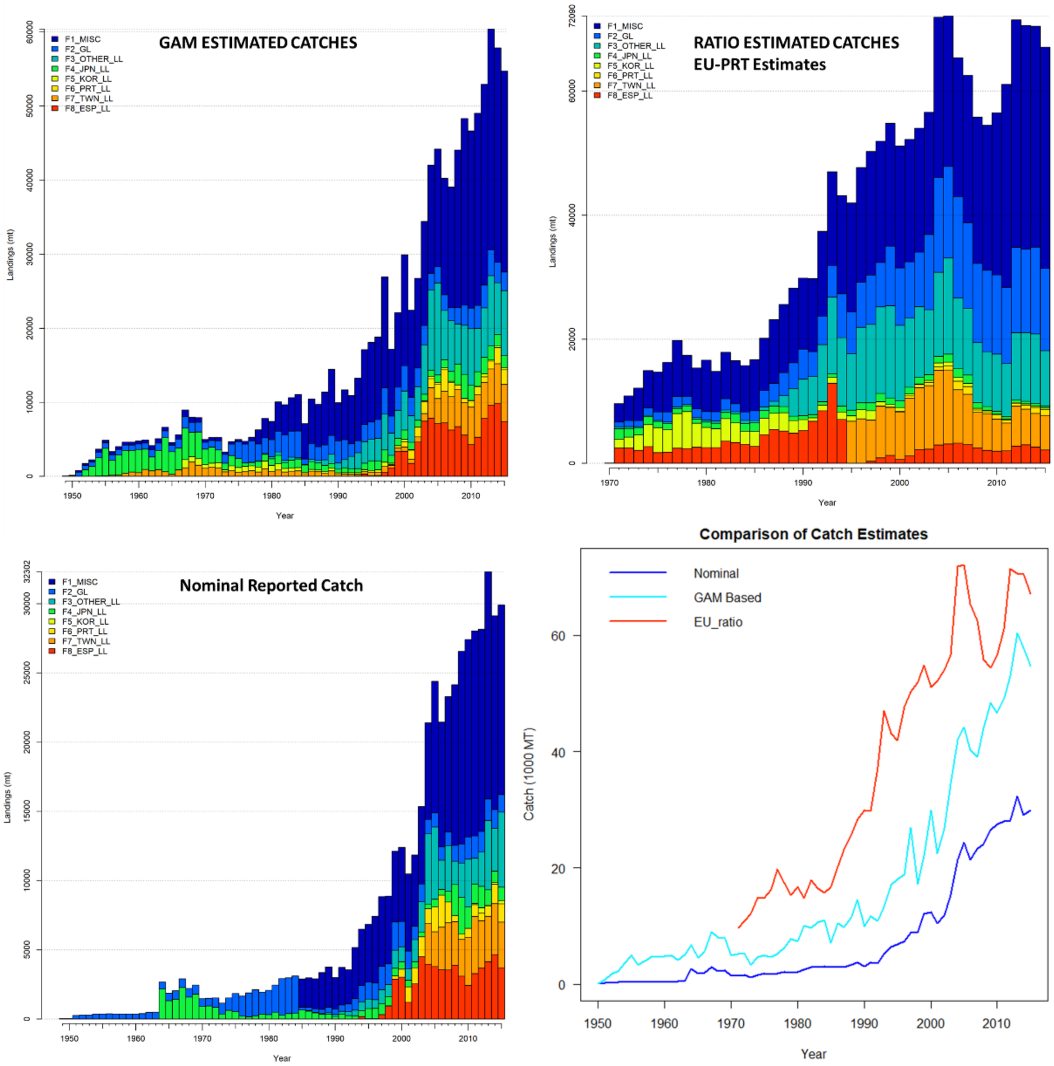

Figure 2 Estimated total blue shark catch in mass by fishery over time for the whole Indian Ocean based on the IOTC database (left hand panel) and based on trade based methods (right hand panel). Note the difference in scale on the y-axis.

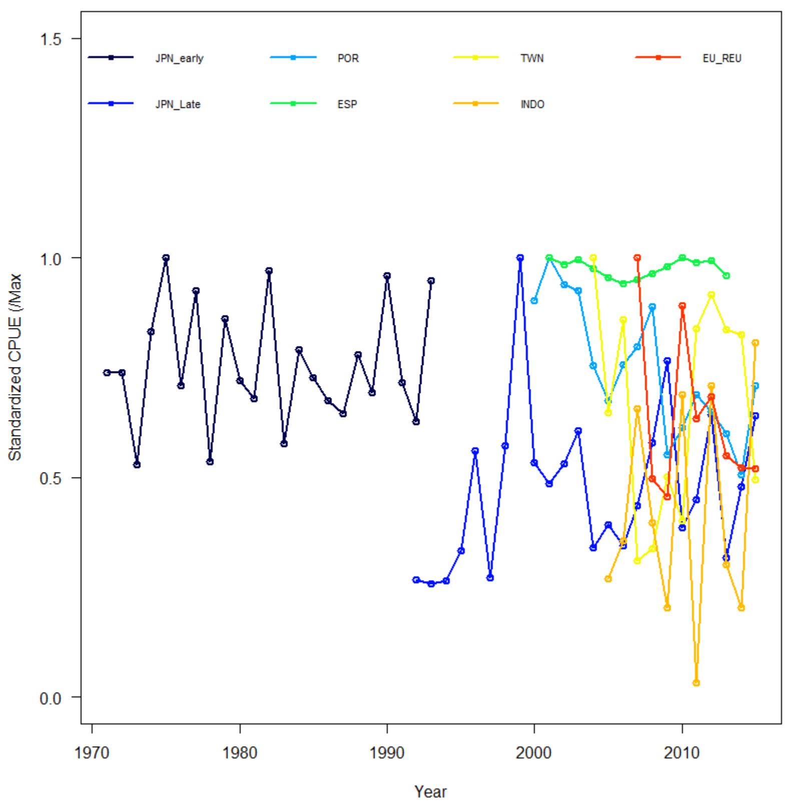

Figure 3. Standardized CPUE for Japanese(early and late), Portuguese, Taiwanese and Spanish , Indonesian, and EU Reunion longline fleets based on papers submitted to WPEB-13. All series have been rescaled by their max so that they are visually comparable for relevant periods of overlap

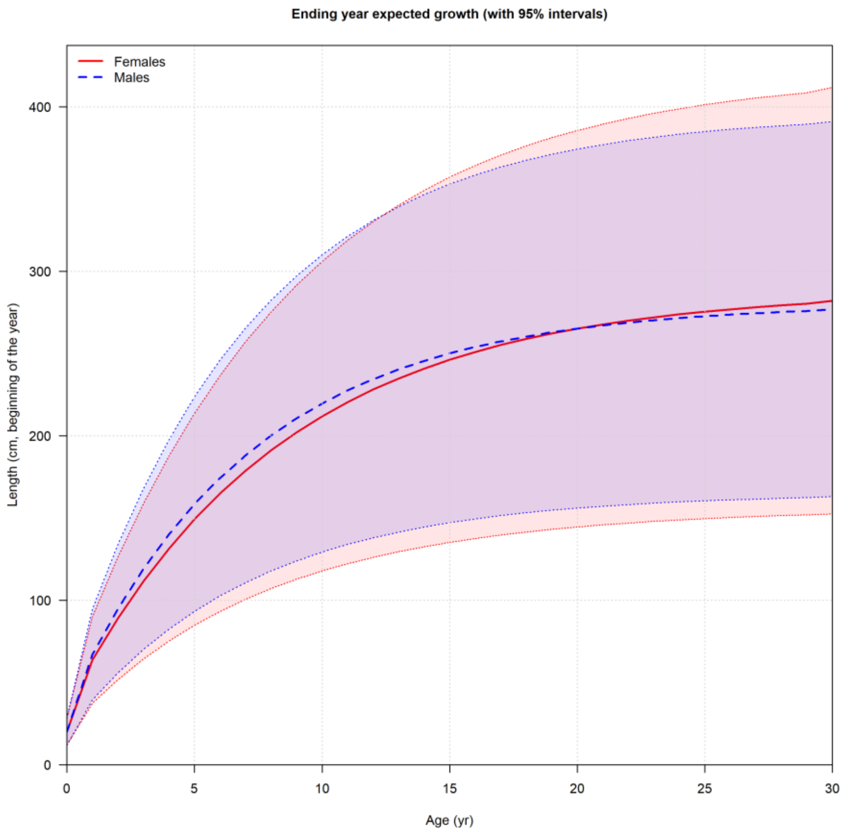

Figure 4. Sex-specific growth curves (from Cohelo et al 2017) calculated based on blue sharks in the Indian Ocean.

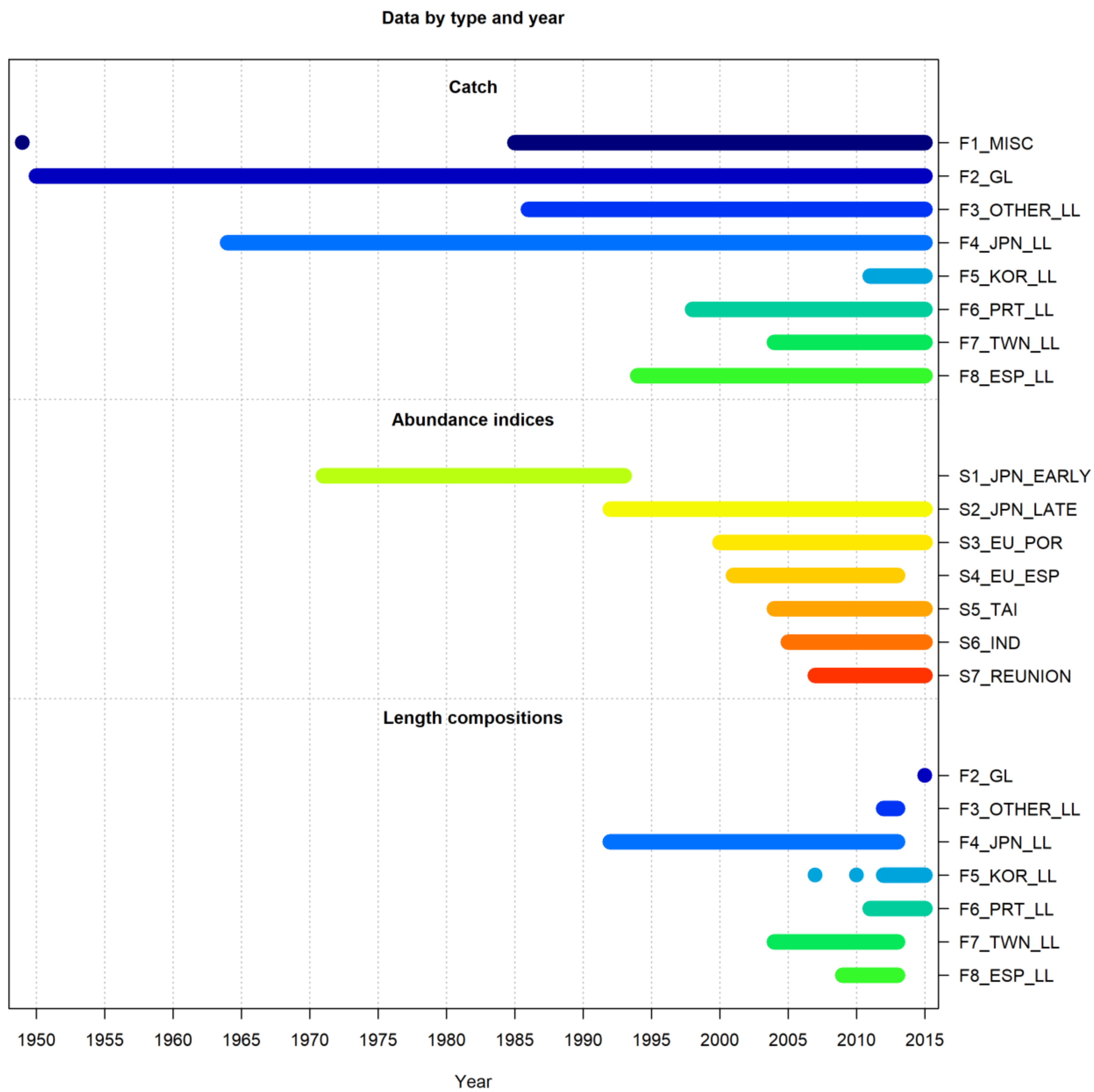

Figure 5: Temporal data coverage for the reference case model for the assessment of blue sharks in the north Pacific.

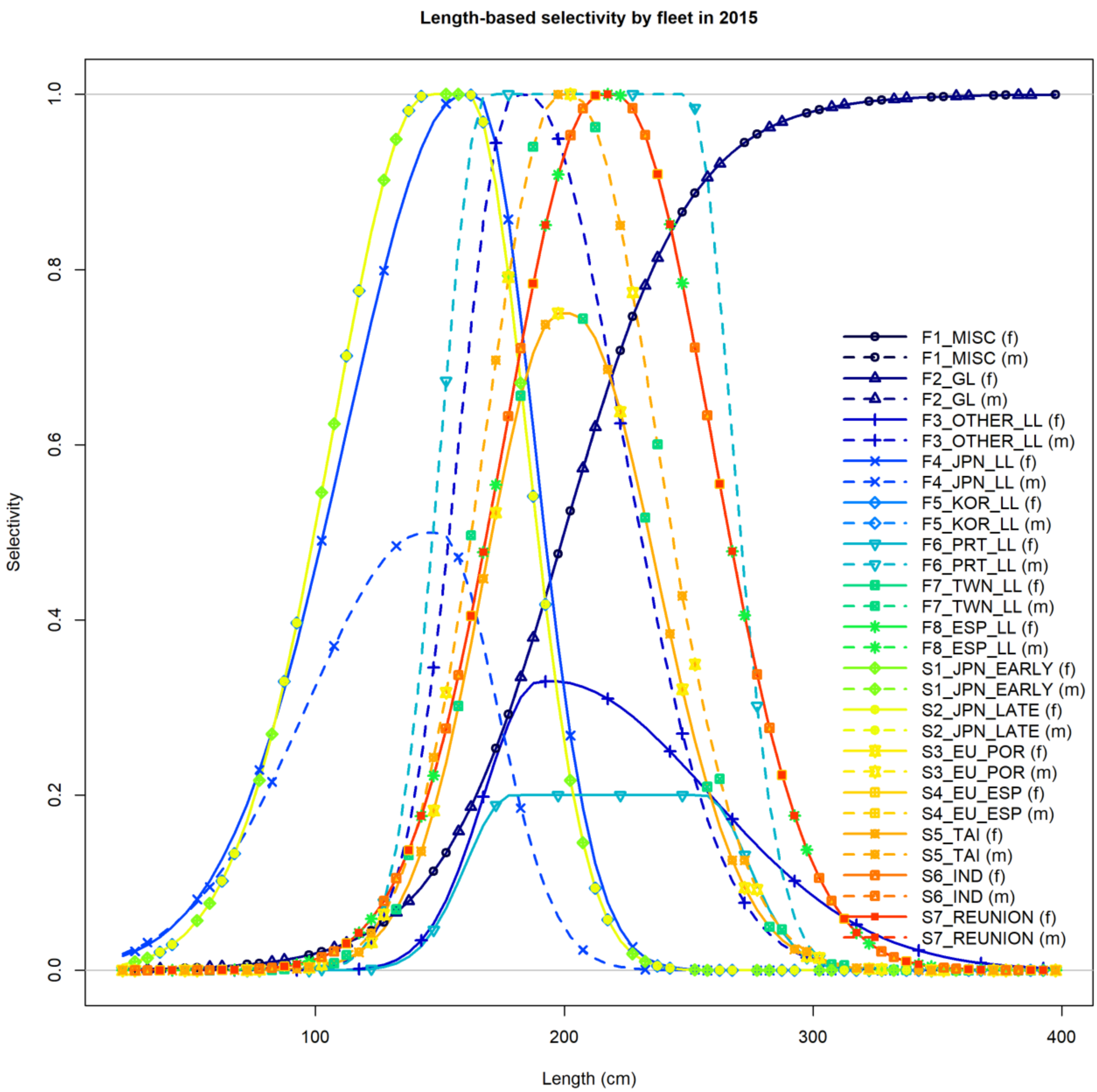

Figure 6: Selectivity curves estimated for female and male from the reference case model for the assessment of blue sharks in the Indian Ocean.

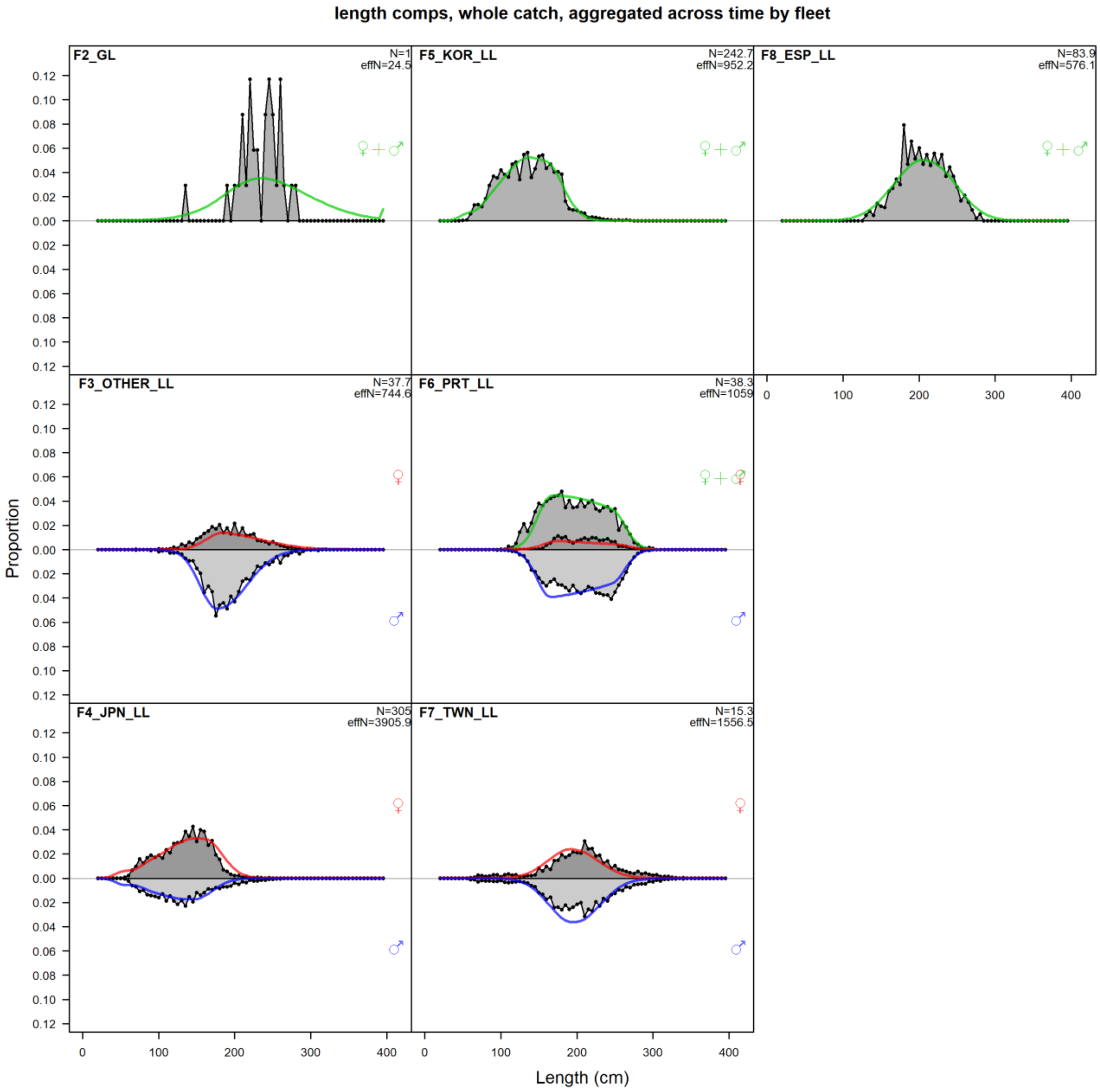

Figure 7 Fit to the female length frequency data for the reference case model for the assessment of blue sharks in the Indian Ocean.

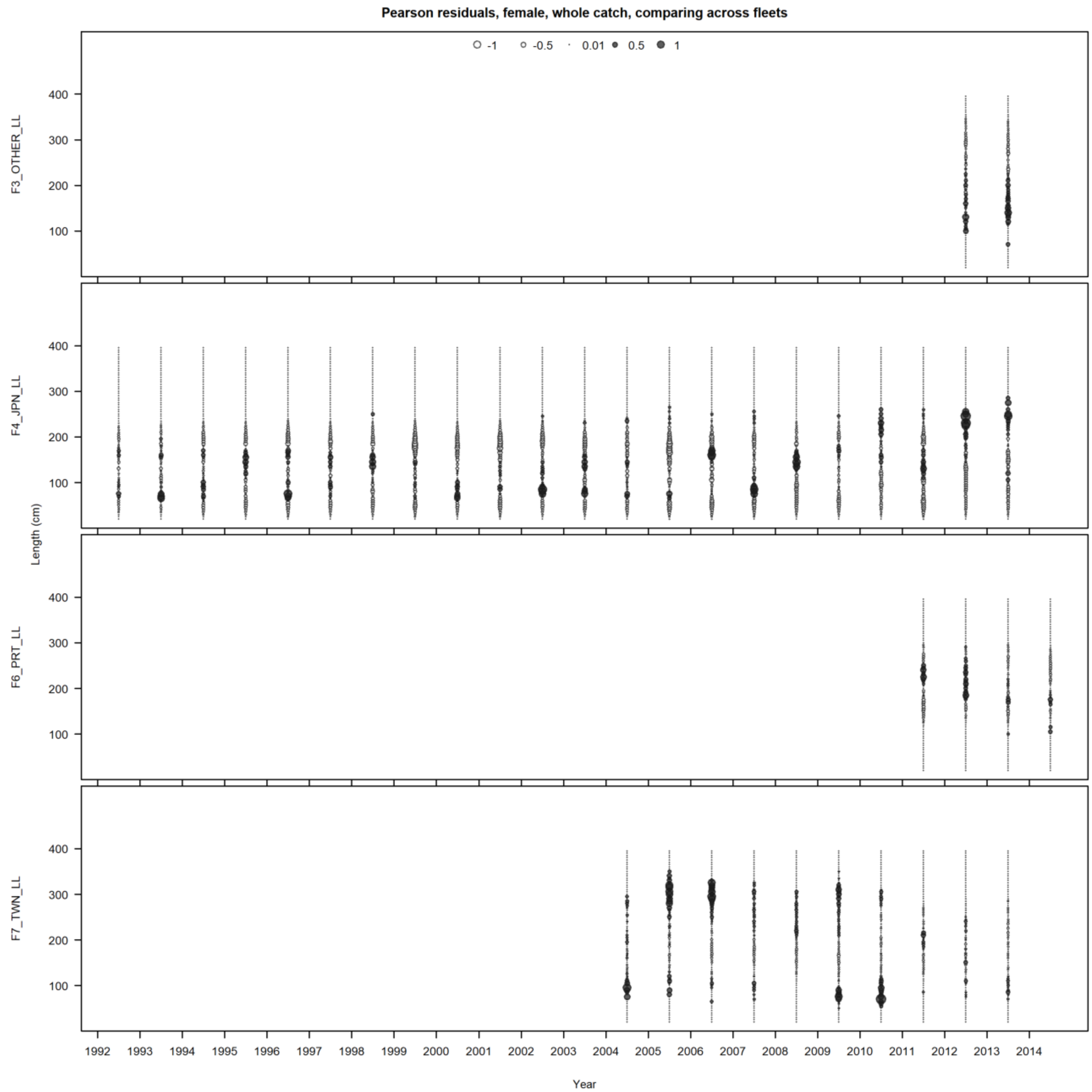

Figure 8 Residuals from the fit to the female length frequency data for the reference case model for the assessment of blue sharks in the Indian Ocean.

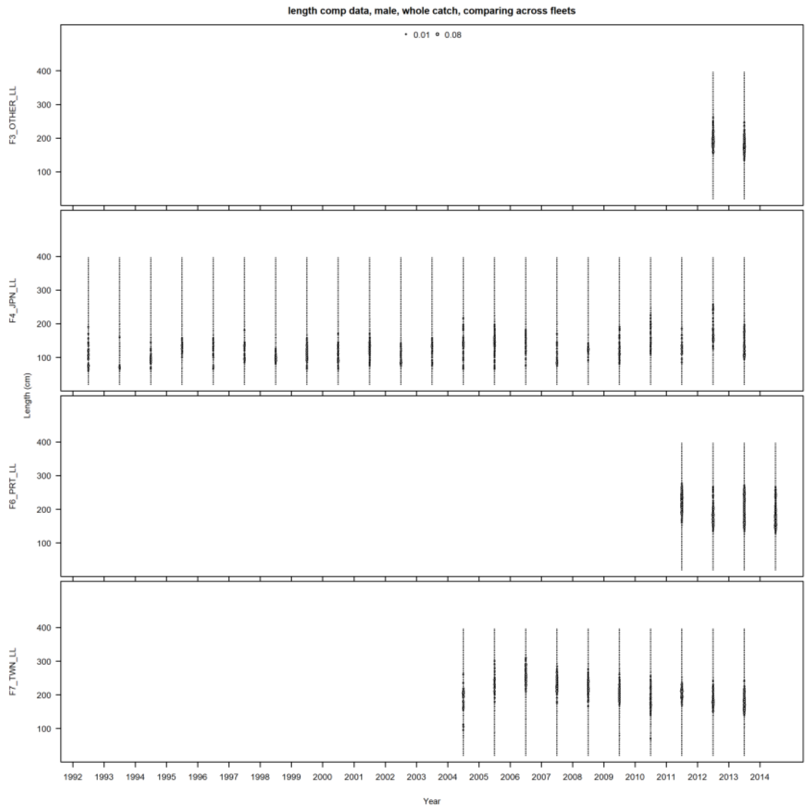

Figure 9 Pearson residuals, comparing across fleets (males). Closed bubbles are positive residuals and open bubbles are negative residuals, bubble sizes are scaled to maximum within each panel.

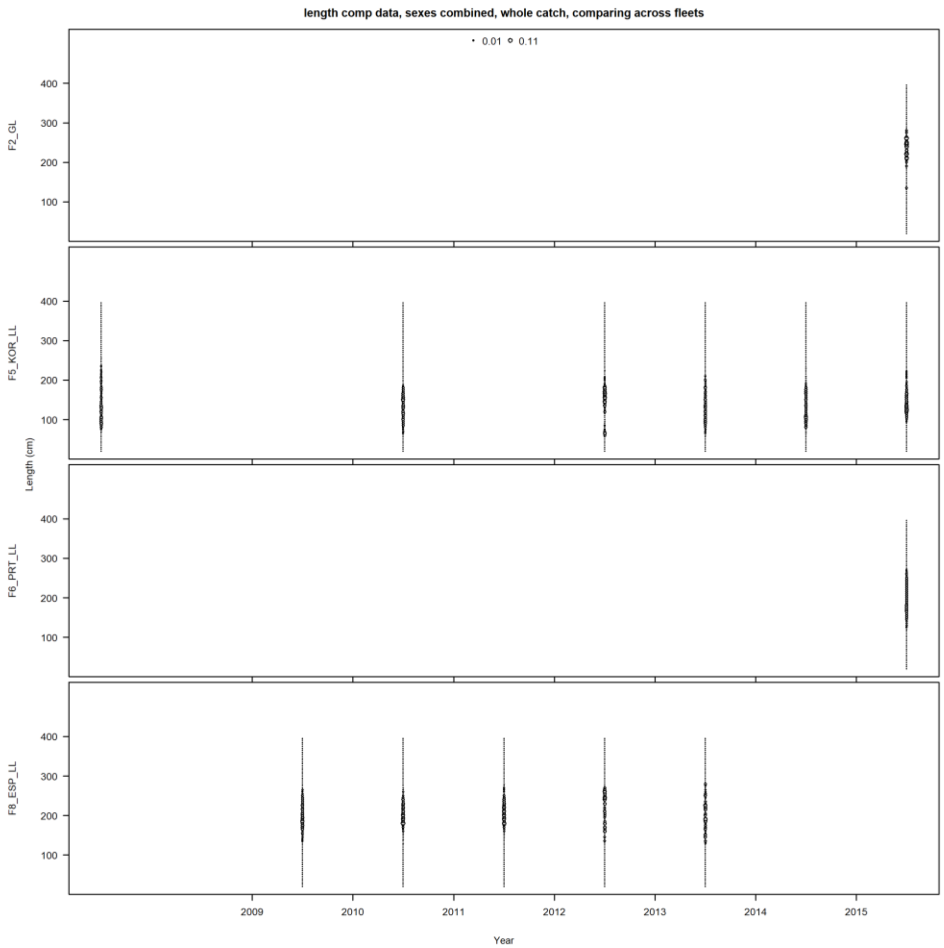

Figure 9a. Pearson residuals, comparing across fleets (sexes combined). Closed bubbles are positive residuals and open bubbles are negative residuals, bubble sizes are scaled to maximum within each panel. Thus, comparisons across panels should focus on patterns, not bubble sizes.

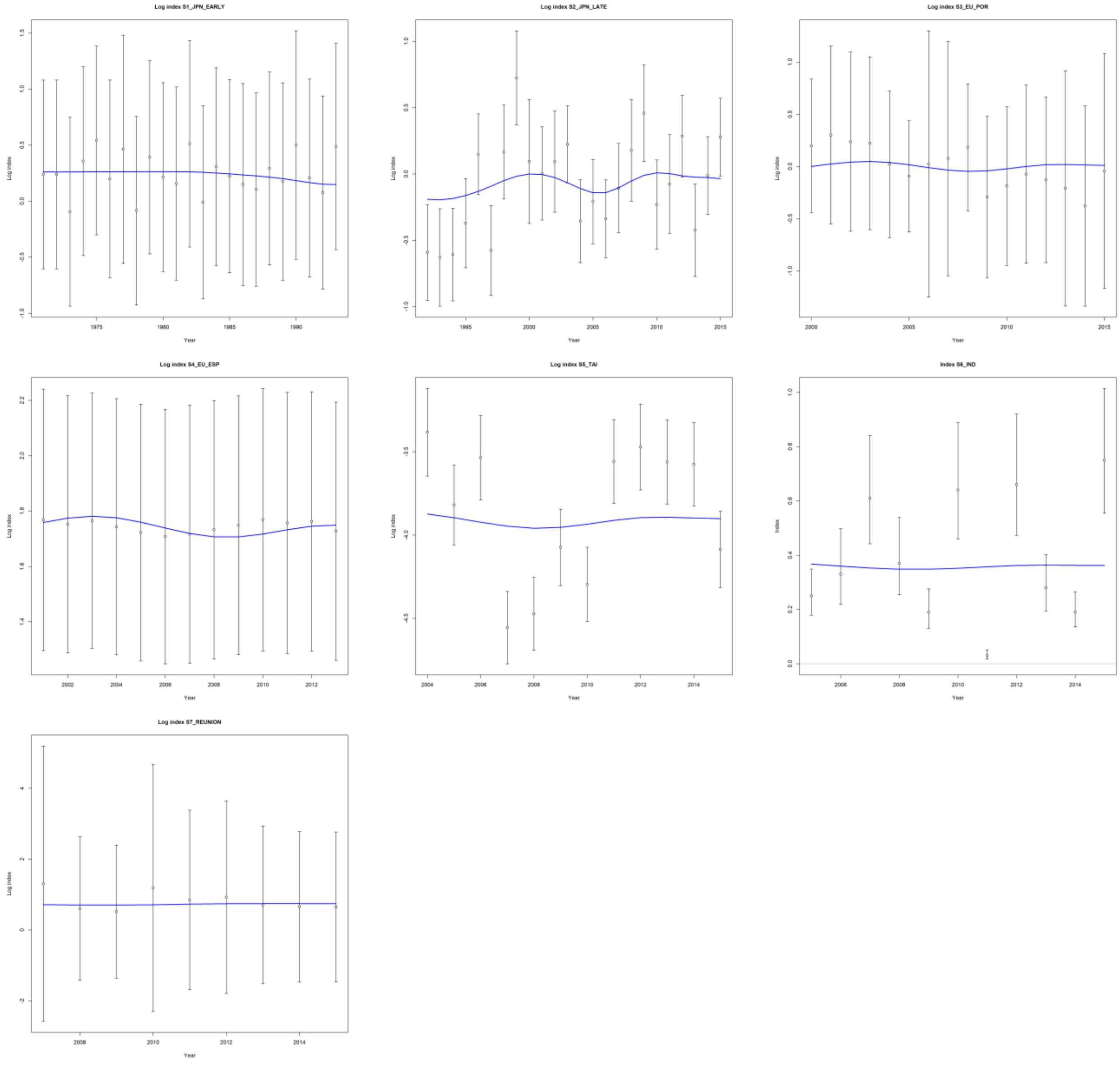

Figure 10: Reference case fit to the CPUE series, presented on a log scale. Note that the reference case included all of the CPUE series fit at the same time.

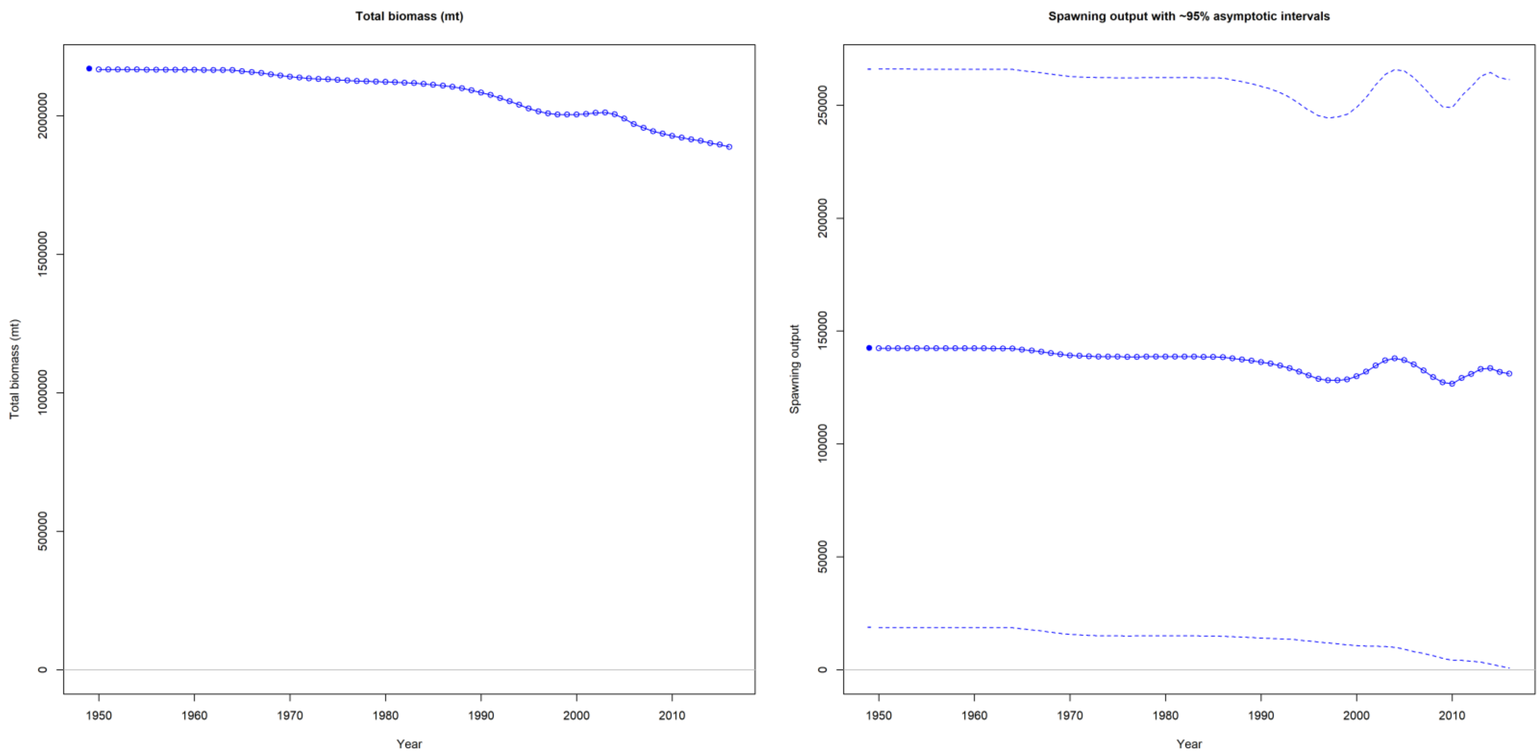

Figure 11: Total biomass (left) and spawning potential (output) for the reference case parameterization model. The filled dot represents the pre-model estimate of unfished biomass and unfished spawning potential (output).

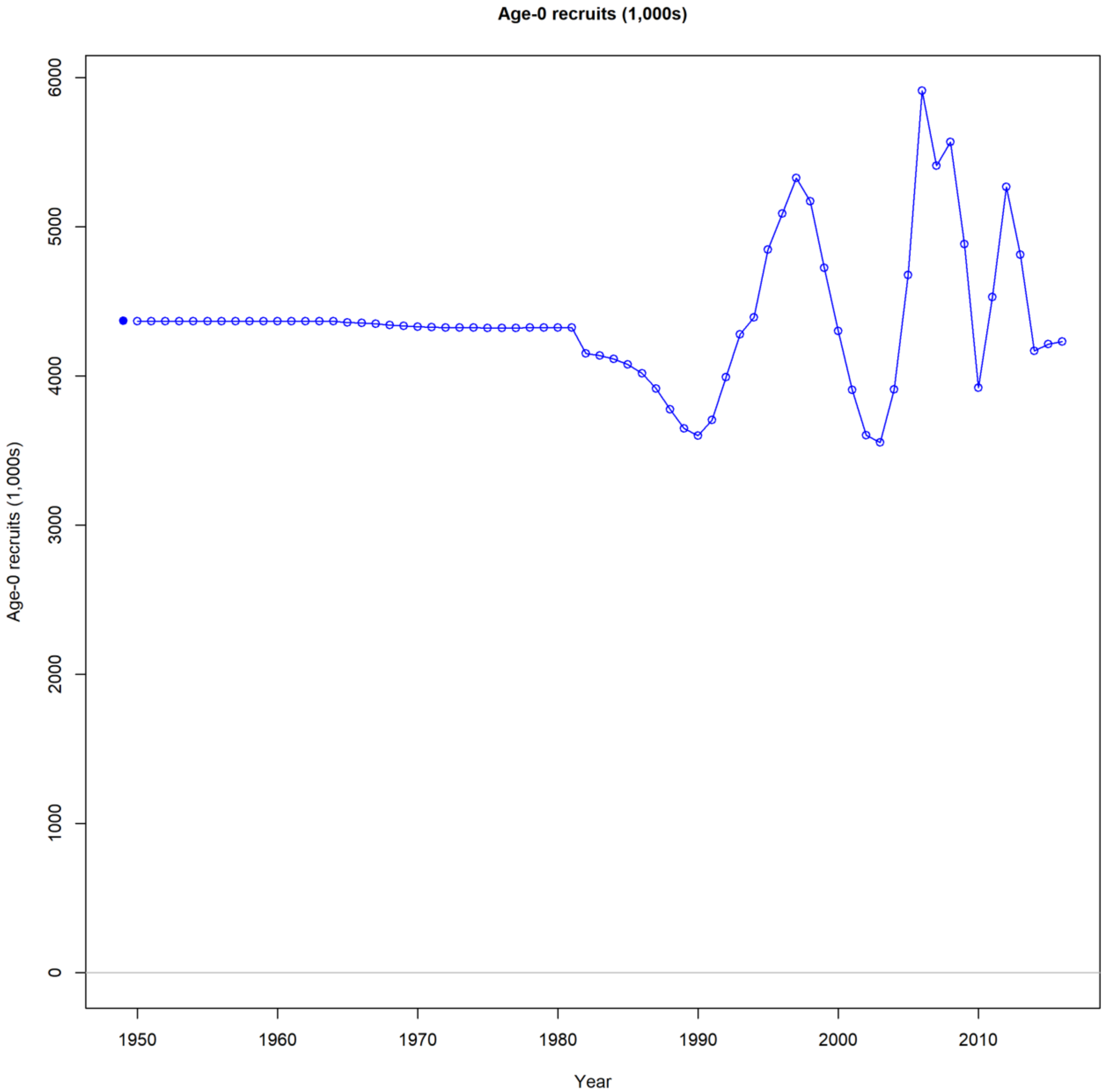

Figure 12 .Estimated recruitment including the estimate of virgin recruitment (filled circle at the start of the time series) for the reference case model for the assessment of blue sharks in the Indian Ocean.

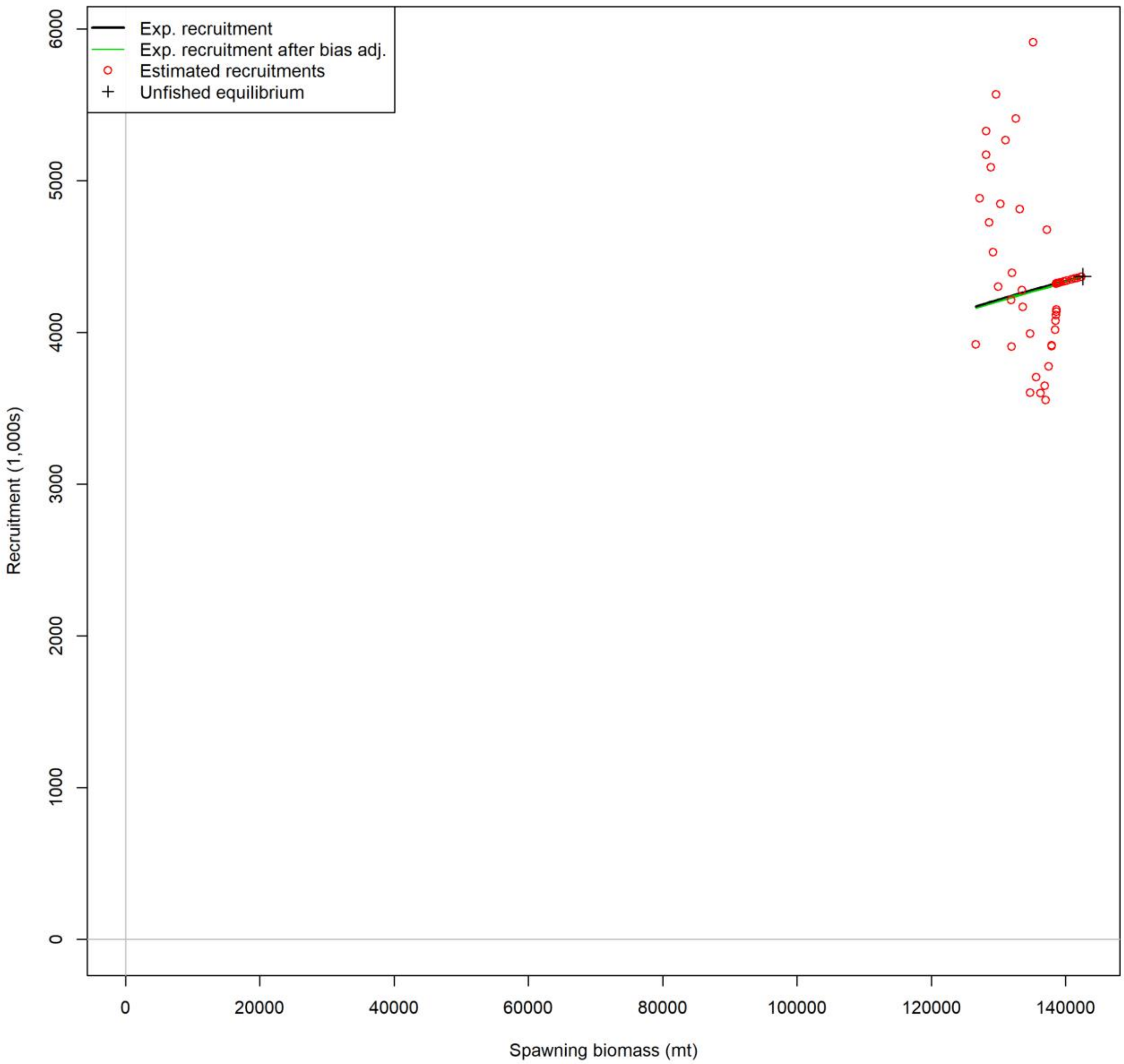

Figure 13 Stock recruitment curve used in the assessment and time series of estimates (red points).

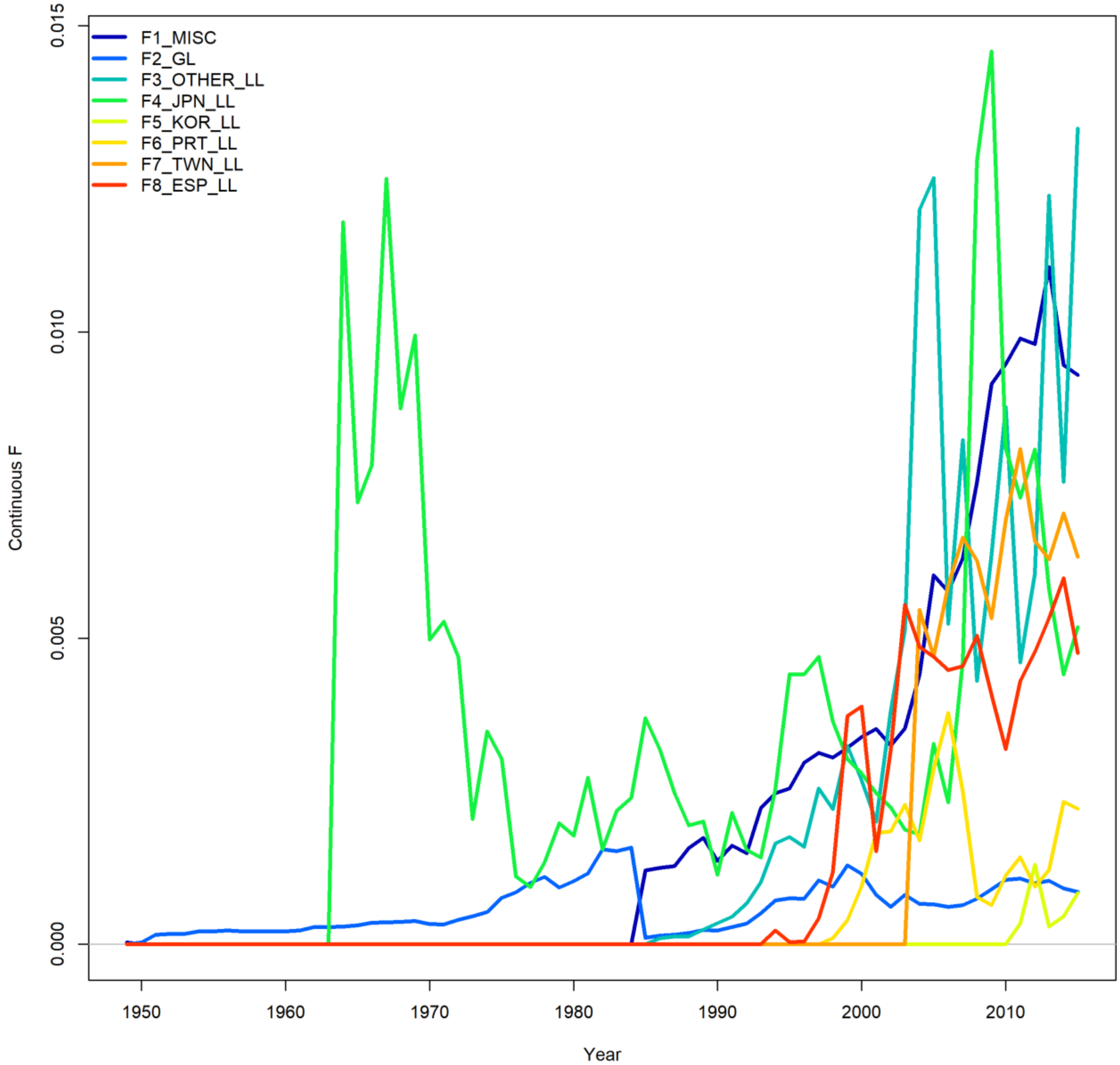

Figure 14 Estimated fishing mortality for each fleet in the assessment.

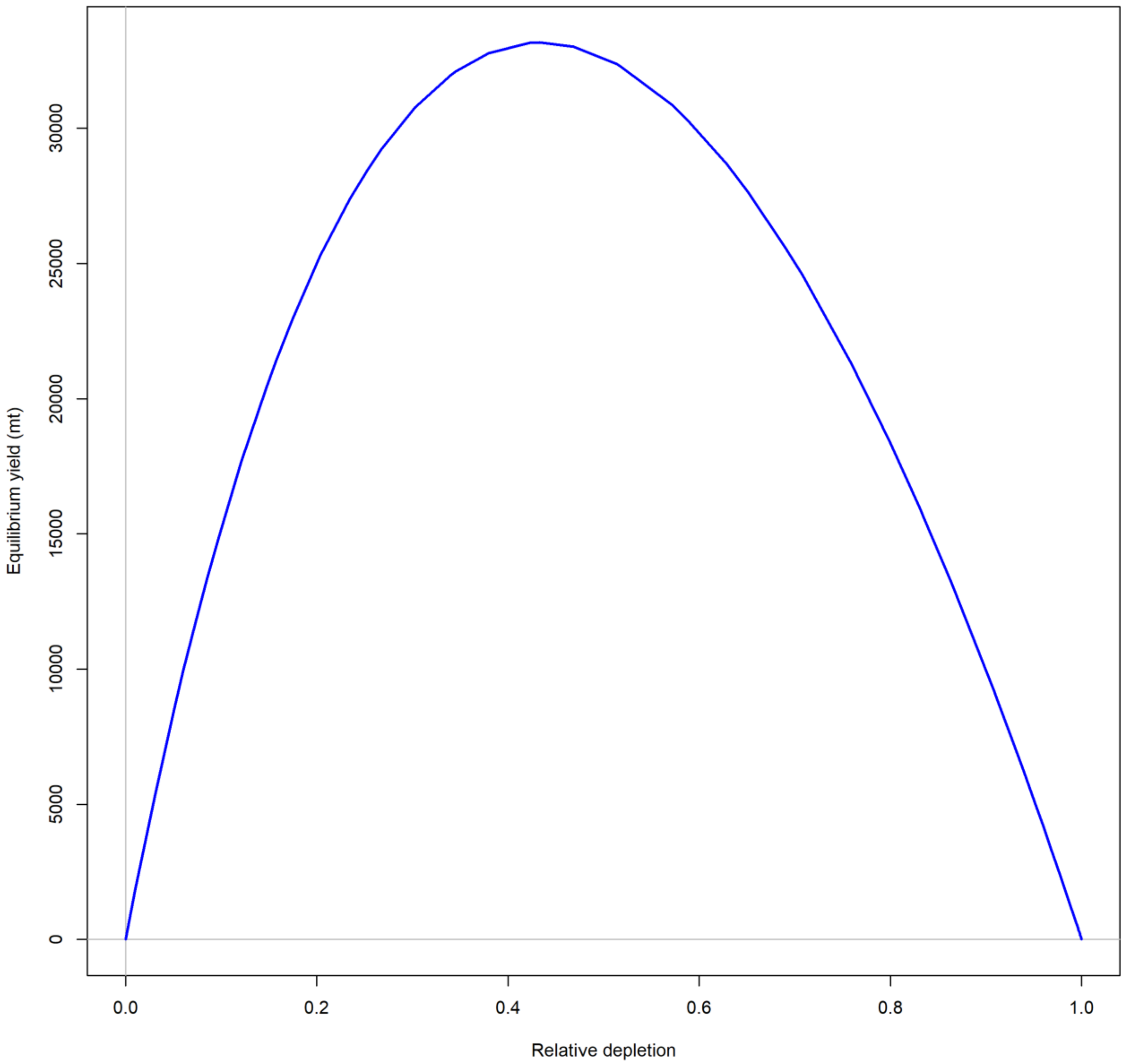

Figure 15. Equilibrium yield curve for the reference case model for the assessment of blue sharks in the Indian Ocean.

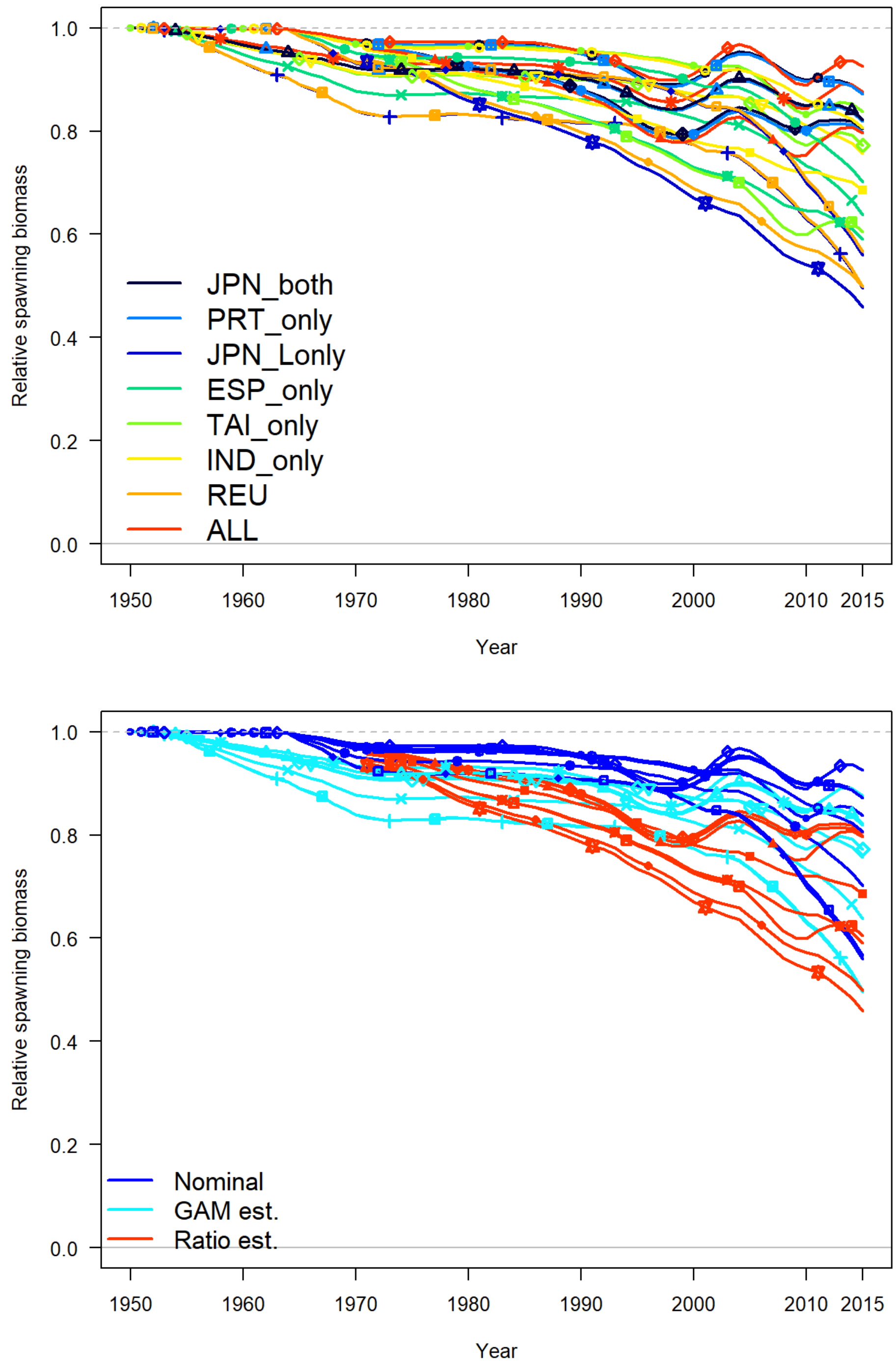

Figure 18 Spawning biomass depletion for all runs in the grid of sensitivities. The top panel shows the depletion based on the different CPUE series used and the bottom panel shows the results based on the catch series used.

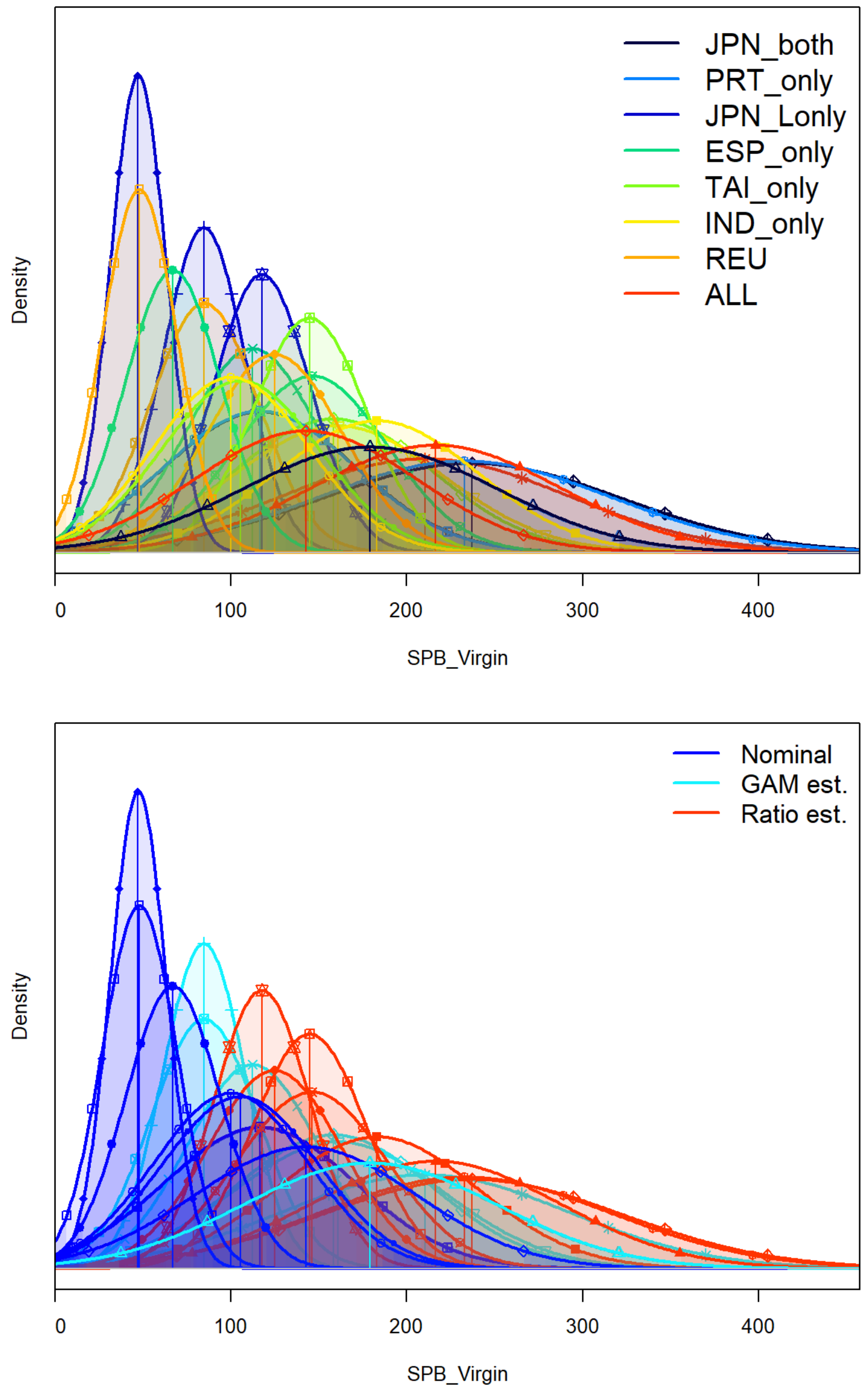

Figure 18 Density estimates for the virgin spawning biomass from all runs in the grid of sensitivities. The top panel shows the estimates based on the different CPUEs used while the bottom panel shows the estimates based on the different catch estimates used.

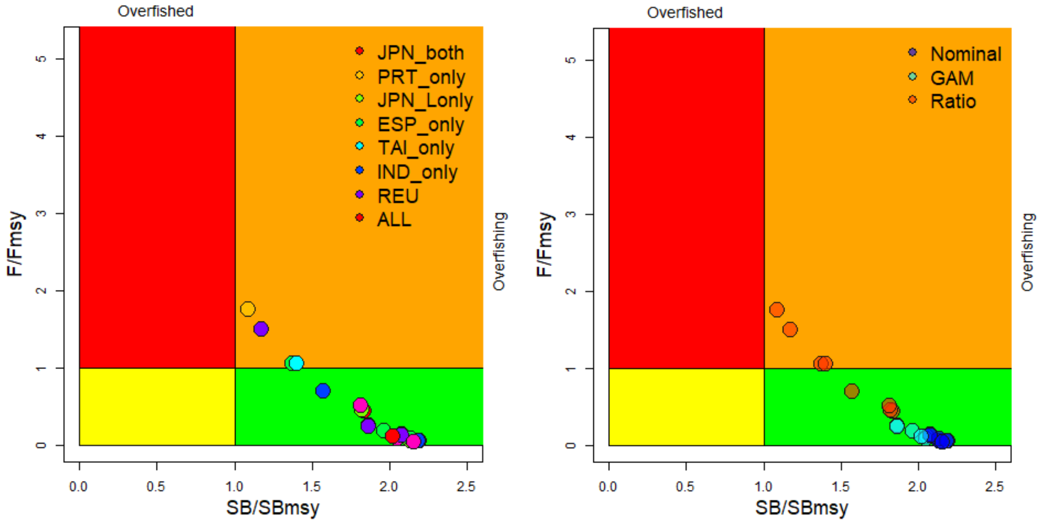

Figure 16. Kobe plot showing the results the estimation of SB/SB$_{MSY}$ and F/F$_{MSY}$, for the terminal year of the model (2015). The left column is coloured according to the CPUE series used and the Right hand side is coloured based on the catch estimates used.