PRELIMINARY STOCK ASSESSMENT OF INDIAN OCEAN SWORDFISH (*Xiphias gladius*) USING THE BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL *JABBA*

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SUMMARY

Bayesian State-Space Surplus Production Models were fitted to Indian Ocean swordfish (*Xiphias gladius*) catch and CPUE data using the 'JABBA' R package. This document presents details on the model diagnostics and stock status estimates for a single 'Reference' model with a prior distribution for r of $log(r) \sim N(log(0.42),0.4)$ and a fixed input value of B_{MSY}/K = 0.4 (Pella-Tomlinson model type). Generally, the CPUE indices were consistent in showing a period of decline from early 1990s until mid-2000s, thereafter stabilizing and even increasing in the northeast and northwest areas. The model fit the CPUE data reasonably well (RMSE = 20.7%) with marginal data conflict between the CPUE indices in the last 5 years. The *MSY* estimate was 30,630 metric tons, which is very similar to the current catch (catch$_{2018}$: 30,686 metric tons) and the current estimate of biomass as a proportion of "pristine" biomass was B_{2018}/K = 0.47. Results from the Reference Model indicate that there is an 81% probability that the swordfish stock status currently falls within the green quadrant of the Kobe biplot ($B_{2018}>B_{MSY}$ and $F_{2018}<F_{MSY}$). A retrospective analysis indicated a negligible retrospective pattern, and hindcasting cross-validation results suggested that the model has good prediction skill (*MASE* = 0.72). Various scenarios of CPUE input data were explored using a sensitivity analysis, and the trends in biomass and stock status estimates were fairly insensitive to variations in CPUE input data. Notably, the inclusion of all of the available CPUE indices produced estimates that were the most similar to the Reference Model, while the inclusion of the Indonesian CPUE index produced the most pessimistic results.

KEYWORDS

stock status, CPUE fits,
hindcast, surplus production function, sensitivity

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1. Introduction

The broadbill swordfish (*Xiphias gladius*) is the most widely distributed of the billfish species. They are highly fecund, migratory fish that grow quickly in the early years and reach their maximum size at approximately 15 years. Swordfish do not school, but regularly move between surface waters and great depths (Ward & Elscot 2000). There is also evidence to suggest genetic distinction exists within the Indian Ocean, and the stock structure of this species continues to be investigated.

Historically, swordfish in the Indian Ocean were predominantly caught by the Japan and Taiwan longline fisheries as bycatch, so catches remained low between 1950 and 1990. With the development of the Fresh Tuna longline fishery in the late 1980s, catches increased sharply (from around 8,000 t in 1991 to 36,000 t in 1998) as the Japanese and Taiwanese longline fleet started targeting the species. This coincided with the development of longline fisheries in Australia, France, Seychelles and Mauritius and arrival of distant longline fleets to the Atlantic Ocean, i.e., EU-Portugal, EU-Spain (IOTC, 2017). To date, swordfish remain a high value catch that represent an increasingly important source to many coastal nations in Indian Ocean.

In 2017, the Indian Ocean Commission (IOTC) carried out an assessment for swordfish by employing four different model types; the spatially disaggregated, sex explicit, and age structured model Stock Synthesis 3 (SS3; Methot and Wetzel, 2013), a non-equilibrium production model (A Stock Production Model Incorporating Covariates, ASPIC; Prager 1994), customized Bayesian State Space Production Model (BSPM) with process error (Andrade 2016), and a Statistical-Catch-At-Age (SCAA) model. Management advice was based on the results from the Stock Synthesis Model, which indicated that spawning stock biomass in 2015 was estimated to be 26–43% of the unfished levels. The stock was determined to not be overfished and not subject to overfishing.

Considering results from multiple model structures, ranging from simple to complex, allows for exploring different assumptions and, ultimately, a better understanding of the stock status. With this in mind, we present a stock assessment for the Indian Ocean swordfish stock based on the Bayesian state-space surplus production model framework, JABBA (Just Another Bayesian Biomass Assessment; Winker et al., 2018a), using updated catch and standardized longline CPUE time series through 2018. JABBA has been applied in a number of recent IOTC billfish stock assessments, including blue marlin (Parker et al., 2019a,b), black marlin (Parker et al., 2018a) and striped marlin (Parker et el., 2018b).

2. Material and Methods

2.1. *JABBA inputs*

This stock assessment is implemented using the Bayesian state-space surplus production model framework JABBA (Winker et al., 2018), which is now available as 'R package' that can be installed from github.com/jabbamodel/JABBA. JABBA's inbuilt options include: (1) automatic fitting of multiple CPUE time series and associated standard errors; (2) estimating or fixing the process variance, (3) optional estimation of additional observation variance for individual or grouped CPUE time series, and (4) specifying a Fox, Schaefer or Pella-Tomlinson production function by setting the inflection point B_{MSY}/K and converting this ratio into a shape parameter m, (5) extensive diagnostic procedures and associated plots (e.g. residual run tests) and (6) a routine to conduct retrospective analysis. A full JABBA model description, including formulation and state-space implementation, prior specification options and diagnostic tools is available in Winker et al. (2018).

2.2. *Fishery data*

Fishery catch data for Indian Ocean swordfish were made available by the IOTC Secretariat for the period 1950-2018 (**Figure 1**). Relative abundance indices were made available in the form of standardized CPUE time series for several fleets. The CPUE time series cover a variety time periods for several fleets, all of which were from longline fleets, as follows:

- Japan 1979-1993 (JPN1) and 1994-2018 (JPN2), disaggregated by area (NE, NW, SE, SW)
- Taiwan 1979-2018, disaggregated by area (NE, NW, SE, SW)
- Spain (2001-2018)
- Portugal (2000-2018)
- Indonesia (2006-2018)
- South Africa (2004-2018)

2.3. *Model specifications*

For the unfished equilibrium biomass *K*, the default settings of the JABBA R package were applied, which is a vaguely informative lognormal prior with a large CV of 100% and a central value that corresponds to eight times the maximum total catch, which is consistent with parameterization procedures followed when using other platforms such as Catch-MSY (Martell and Froese, 2013) or SPiCt (Pederson and Berg 2017). The initial depletion lognormal prior ($\varphi = B_{1950}/K$) was inputted with mean = 1 and CV of 10%, consistent with the low catches reported for the early period (1950s). All catchability parameters were formulated as uninformative uniform priors, while additional observation variances were estimated for each index by assuming inverse-gamma priors to enable model internal variance weighting. Here, the process error of $\log(B_y)$ in year y was estimated “freely” by the model using an uninformative inverse-gamma distribution with both scaling parameters setting at 0.001.

For *r*, a lognormal prior a mean = 0.42 and CV=0.4 was assumed. This was originally developed for South Atlantic swordfish by McAllister (2014) using Leslie matrix population simulations, and later applied by Winker et al. (2018) in the South Atlantic swordfish assessment. The shape of the production function was described by a Pella-Tomlinson production function, so that *MSY* is attained at $B_{\mathrm{MSY}}/K = 0.4$.

2.4. *Model diagnostics*

JABBA is implemented in R (R Development Core Team, https://www.r-project.org/) with a JAGS interface (Plummer, 2003) to estimate the Bayesian posterior distributions of all quantities of interest by means of a Markov Chains Monte Carlo (MCMC) simulation. The JAGS model is executed from R using the wrapper function jags() from the library r2jags (Su and Yajima, 2012), which depends on rjags. In this study, three MCMC chains were used. Each model was run for 30,000 iterations, sampled with a burn-in period of 5,000 for each chain and thinning rate of five iterations. Basic diagnostics of model convergence included visualization of the MCMC chains using MCMC trace-plots as well as Heidelberger and Welch (Heidelberger and Welch, 1992) and Geweke (1992) and Gelman and Rubin (1992) diagnostics as implemented in the coda package (Plummer et al., 2006).

To evaluate CPUE fits, the model predicted CPUE indices were compared to the observed CPUE. JABBA-residual plots were used to examine (1) colour-coded lognormal residuals of observed versus predicted CPUE indices by fleet together with (2) boxplots indicating the median and quantiles of all residuals available for any given year; the area of each box indicates the strength of the discrepancy between CPUE series (larger box means higher degree of conflicting information) and (3) a loess smoother through all residuals which highlights systematically auto-correlated residual patterns to evaluate the randomness of model residuals. In addition it depicts the root-mean-squared-error (RMSE) as a goodness-of-fit statistic. A run test was conducted to quantitatively evaluate the randomness of residuals (Carvalho et al., 2017). The run test diagnostic was applied to residuals of the CPUE fit on log-scale using the function runs.test in the R package tseries, considering the 2-sided p-value of the Wald-Wolfowitz run test. The run test results can be visualized within JABBA using a specifically designed plot function that illustrates which time series passed or failed the run test and highlights individual time-series data points fall outside the three-sigma limits (e.g. Anhøj and Olesen, 2014).

To check for systematic bias in the stock status estimates, a retrospective analysis was performed. This was done by removing one year of data at a time sequentially (n = 8), refitting the model and comparing quantities of interest (i.e. biomass, fishing mortality, B/B_{MSY}, F/F_{MSY}, B/B_0 and MSY) to the Reference Model that is fitted to full time series. To compare the bias between the models, we computed Mohn's (1999) rho (ρ) statistic.

2.5. *CPUE sensitivity runs*

To examine the sensitivity of the assessment results to CPUE input data, several alternative scenarios which varied the fitted CPUE indices were run (**Table 1**). With the exception of CPUE input data, model parameterization remained identical when running these scenarios.

3. Results and Discussion

Catches of swordfish in the Indian Ocean remained low until 1991, increasing substantially thereafter and peaking in 2004 with a total of 40,011 metric tons (**Figure 1**). Previously, a definitive change in targeting after 1993 was identified for the Japanese and Taiwanese longline fleets (Fu et al., 2017), which was evident in preliminary JABBA runs. As such, indices from these two fleets were split into two time periods (1979–1993; 1994–2018). Generally, the indices included in the Reference Model (**Table 1**) were consistent in showing a period of decline from early 1990s until mid-2000s, thereafter stabilizing and even increasing in the northeast and northwest (**Figure 2**). The Reference Model appeared to fit CPUE data reasonably well, and run tests conducted on the log-residuals indicated that only the POR index possibly violated the hypothesis of randomly distributed residual patterns (**Figure 4**). Generally, the goodness-of-fit was adequate (RMSE = 20.7%) with marginal data conflict between CPUE indices in the last 5 years, shown by inflated residual patterns (**Figure 3**). However, there were no notable deviations on the process error (**Figure 3**).

Examination of marginal posterior distributions and prior densities for the Reference Model (**Figure 5**) indicated a median marginal posterior for r of 0.36 and 255,016 metric tons for K. The relatively narrow posterior distribution and the small prior to posterior variance ratio (PPVR) suggest that the data are to some extent informative with respect to K. The extensive prior/posterior overlap, as well as both PPMR and PPVR values close to 1, indicate that the posterior for initial depletion (φ) was largely informed by the prior.

A summary of the Reference Model posterior quantiles for parameters and management quantities of interest are presented in **Table 2.** The *MSY* estimate was 30, 630 metric tons, which is very similar to the current catch (catch_{2018}: 30,686), and accordingly F_{2018}/F_{MSY} = 0.87. The trajectory of B/B_{MSY} showed a sharp decrease from 1990 to the mid-2000s, before stabilizing at a level marginally above B/B_{MSY} = 1 (**Figure 7**). The current estimate of biomass, as a proportion of "pristine" biomass, is B_{2018}/K = 0.47. The F/F_{MSY} increase from 1950 to 1990 was negligible, but this increased rapidly thereafter to reach a peak in 2004 (**Figure 7**). A decrease in F/F_{MSY} was observed from 2005 – 2011, but fishing mortality has steadily increased since to the current estimate F/F_{MSY} = 0.87.

The results of an eight year retrospective analysis applied to the Reference Model (**Figure 8**) show a negligible retrospective pattern for the first 5 years (2013-2017). However, the sequential removal of years 2012, 2011 and 2010 produce deviations of increasing magnitude. The estimated Mohn's rho for B (rho = -0.11) and B/B_{MSY} (rho = -0.02) fell within the acceptable range of -0.15 and 0.20 (Hurtado-Ferro et al. 2014; Carvalho et al. 2017) and confirm the absence of an undesirable retrospective pattern. Hindcasting cross-validation results for the JPN2_NW index suggests that the model has good prediction skill as judged by the MASE scores of approximately 0.72 (**Figure 6**), which indicates that future projections are consistent with reality of model-based scientific advice.

The surplus production phase plot for the Reference Model corroborated that the stock was likely being overfished for a very brief period (2003-2006), however catches returned to below the surplus production curve relatively quickly (**Figure 9**). Accordingly, the Kobe biplot indicates that the stock briefly entered the orange quadrant, but throughout the time series has never fallen within the red quadrant (**Figure 9**). The Reference Model indicates that there is an 81% probability that the swordfish stock status currently falls within the green quadrant of the Kobe biplot ($B_{2018}>B_{MSY}$ and $F_{2018}<F_{MSY}$).

Various scenarios of differing CPUE input data (**Table 1**) were explored using a sensitivity analysis (**Figure 10).** Notably, the inclusion of all of the available CPUE indices (All) produced B/B_{MSY} and F/F_{MSY} estimates that were the most similar to the Reference Model. This scenario (All) also provided trends in absolute biomass (*B*) that were most similar to those produced by the scenario that included the Japanese historical CPUE data (JPN_Hist) – both of these scenarios produced the lowest *K* values which may be a more accurate representation of the unfished stock. The inclusion of the Indonesian CPUE index (North_IND) in place of the northern Japanese indices produced the most pessimistic results. By contrast, the most optimistic results were derived from scenarios which substituted the Taiwanese indices in place of the Japanese within the Reference Model for all areas (TWN_Ref) and for just the eastern Indian Ocean areas (JPNnorth+TWNeast+Por).

The results suggest that the Reference Model provides a reasonably robust fit to the data as judged by the presented model diagnostics. The trends in biomass and stock status estimates were fairly insensitive to variations in CPUE input data, and the consistency observed in the retrospective analysis results provides a degree of confidence in the predictive capabilities of the assessment of the Indian Ocean swordfish stock using JABBA. The stock status estimates of this assessment are comparable to those of the 2017 assessments using SS3 (base case: Grid-rNTP; Fu et al., 2017) and ASPIC (Wang, 2017), but are more optimistic than the 2017 assessments that used BSPM (Andrade, 2017) and SCAA (Nishida and Yokoi, 2017).

4. Acknowledgements

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5. References

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6. Tables

Table 1 - Summary of sensitivity analyses, which include various CPUE indices that were applied to the Indian Ocean swordfish assessment.

Scenario	Index (years)
Reference Model	JPN-NE (1994-2018) JPN-NW (1994-2018) JPN-SE (1994-2018) JPN-SW (1994-1999) POR (2000-2018)
TWN_Ref	TWN-NE (1994-2018) TWN-NW (1994-2018) TWN-SE (1994-2018) TWN-SW (1994-1999) POR (2000-2018)
JPN_Hist	JPN-NE (1979-2018) JPN-NW (1979-2018) JPN-SE (1979-2018) JPN-SW (1979-1999) POR (2000-2018)
Ref+All	JPN-NE (1994-2018) JPN-NW (1994-2018) JPN-SE (1994-2018) JPN-SW (1994-1999) POR (2000-2018) SPN (2001-2018) IDN (2006-2018) ZAF (2004-2018)
North_IND	JPN-SE (1994-2018) JPN-SW (1994-1999) POR (2000-2018) IDN (2004-2018)
JPNnorth+TWNeast+Por	TWN-NE (1994-2018) JPN-NW (1994-2018) TWN-SE (1994-2018) JPN-NE (1994-2018) POR (2000-2018)
All	JPN-NE (1994-2018) JPN-NW (1994-2018) JPN-SE (1994-2018) JPN-SW (1994-2018) TWN-NE (1994-2018) TWN-NW (1994-2018) TWN-SE (1994-2018) TWN-SW (1994-2018) POR (2000-2018) SPN (2001-2018) IDN (2006-2018) ZAF (2004-2018)

Table 2 - Summary of posterior quantiles presented in the form of marginal posterior medians and associated the 95% credibility intervals of parameters for the Bayesian state-space surplus production Reference Model for the Indian Ocean swordfish.

Estimates	*Reference Model*		
	Median	LCI (2.50%)	UCI (97.50%)
K	255016	161823	399048
r	0.358	0.224	0.574
ψ*(psi)*	1.000	0.824	1.209
σ_{proc}	0.042	0.019	0.093
F_{MSY}	0.302	0.188	0.483
B_{MSY}	102002	64726	159612
MSY	30630	27214	35692
B_{1950}/K	0.999	0.803	1.237
B_{2018}/K	0.465	0.357	0.588
B_{2018}/B_{MSY}	1.163	0.893	1.469
F_{2018}/F_{MSY}	0.866	0.606	1.195

7. Figures

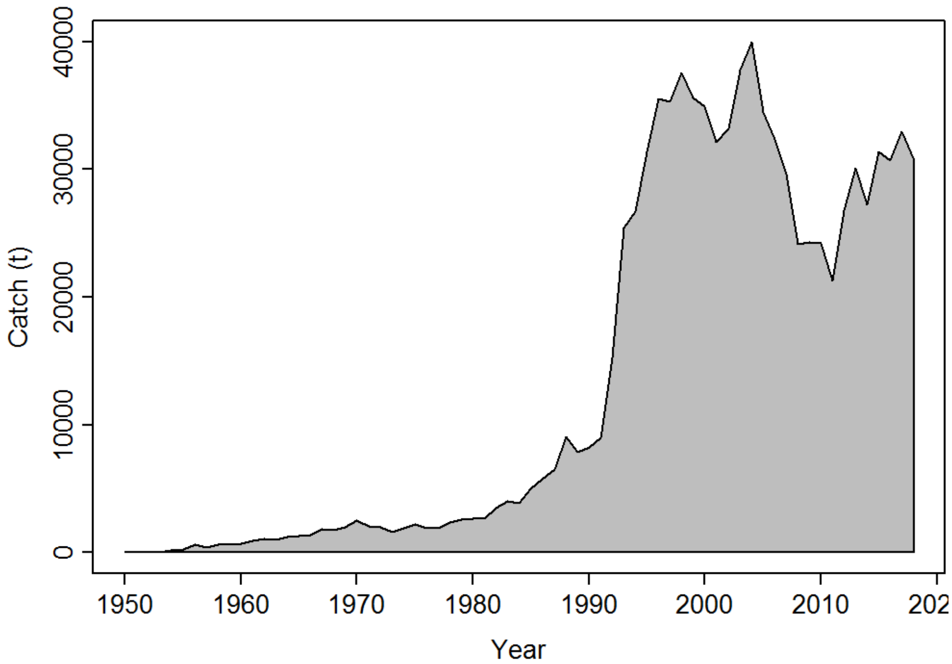


Figure 1 - Available catch times series in metric tons (t) for Indian Ocean swordfish.

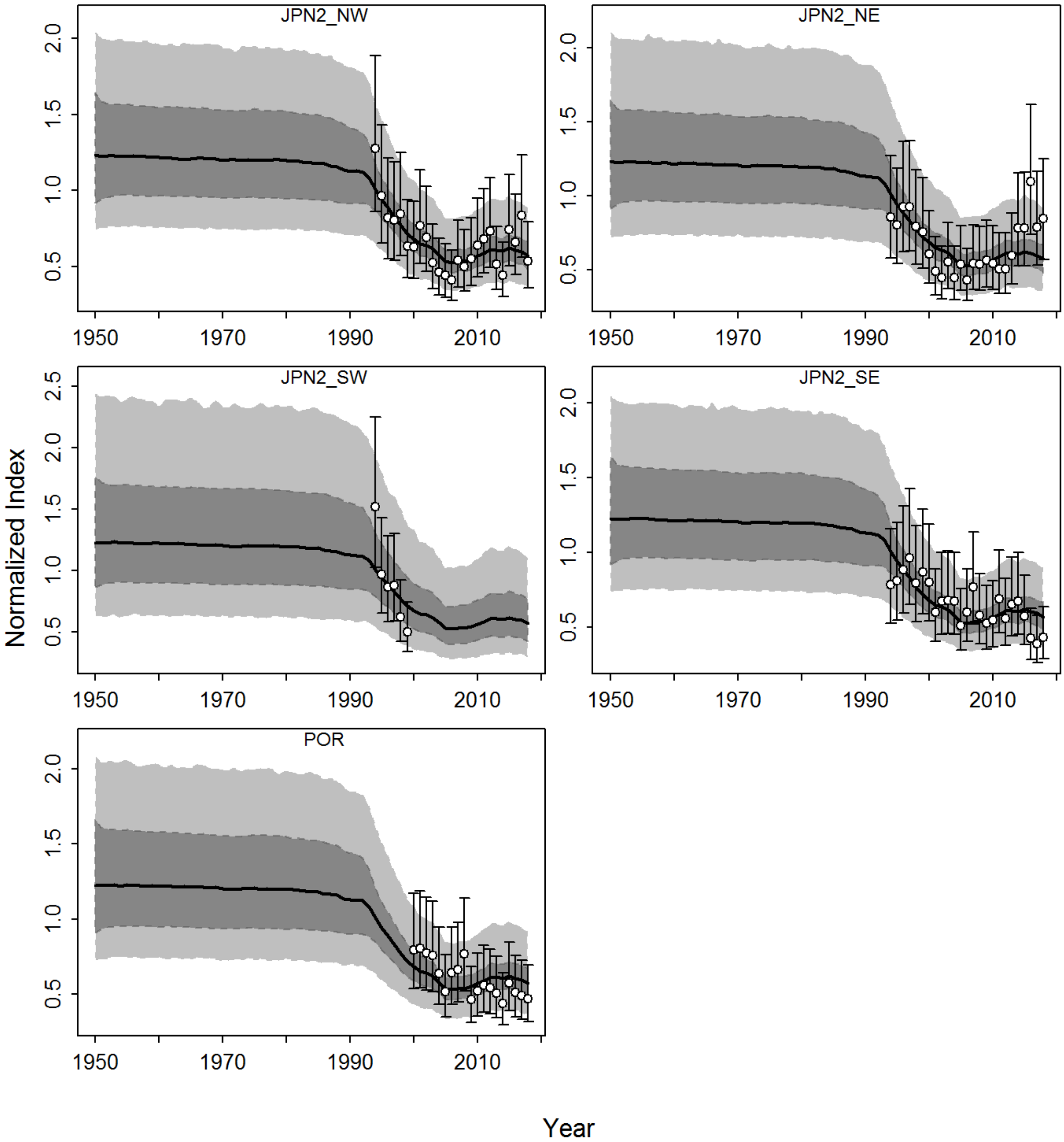
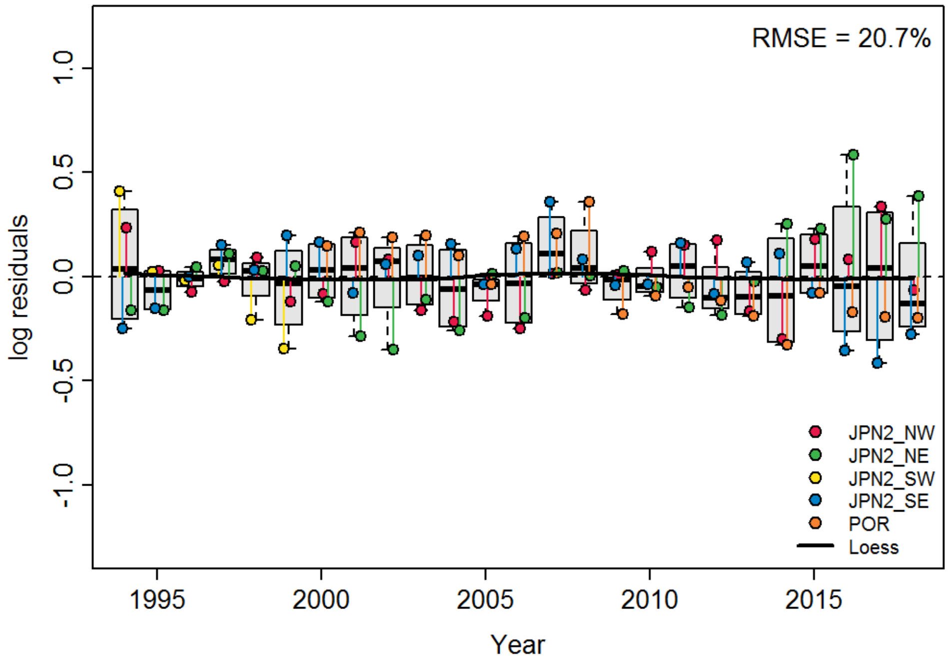


Figure 2 - Time-series of observed (circle) with error 95% CIs (error bars) and predicted (solid line) CPUE of Indian Ocean swordfish for the Bayesian state-space surplus production model JABBA for the Reference Model. The Dark shaded grey areas show 95% credibility intervals of the expected mean CPUE and light shaded grey area denote the 95% posterior predictive distribution intervals.



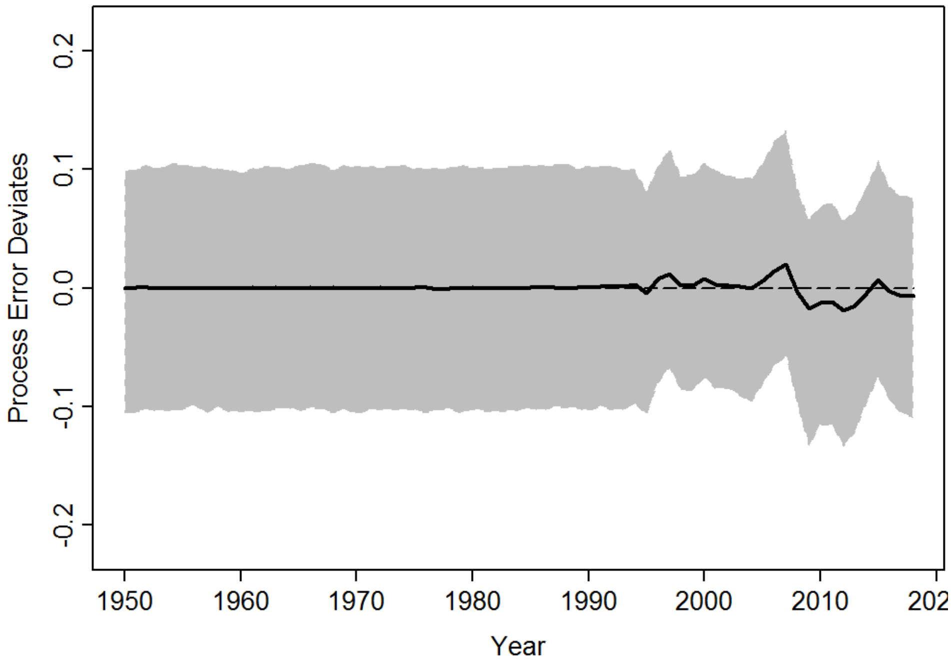


Figure 3 - JABBA residual diagnostic plots of CPUE indices included in the Reference Model for Indian Ocean swordfish. Top panel: Boxplots indicating the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals. Bottom panel: Process error deviates (median: solid line) with shaded grey area indicating 95% credibility intervals.

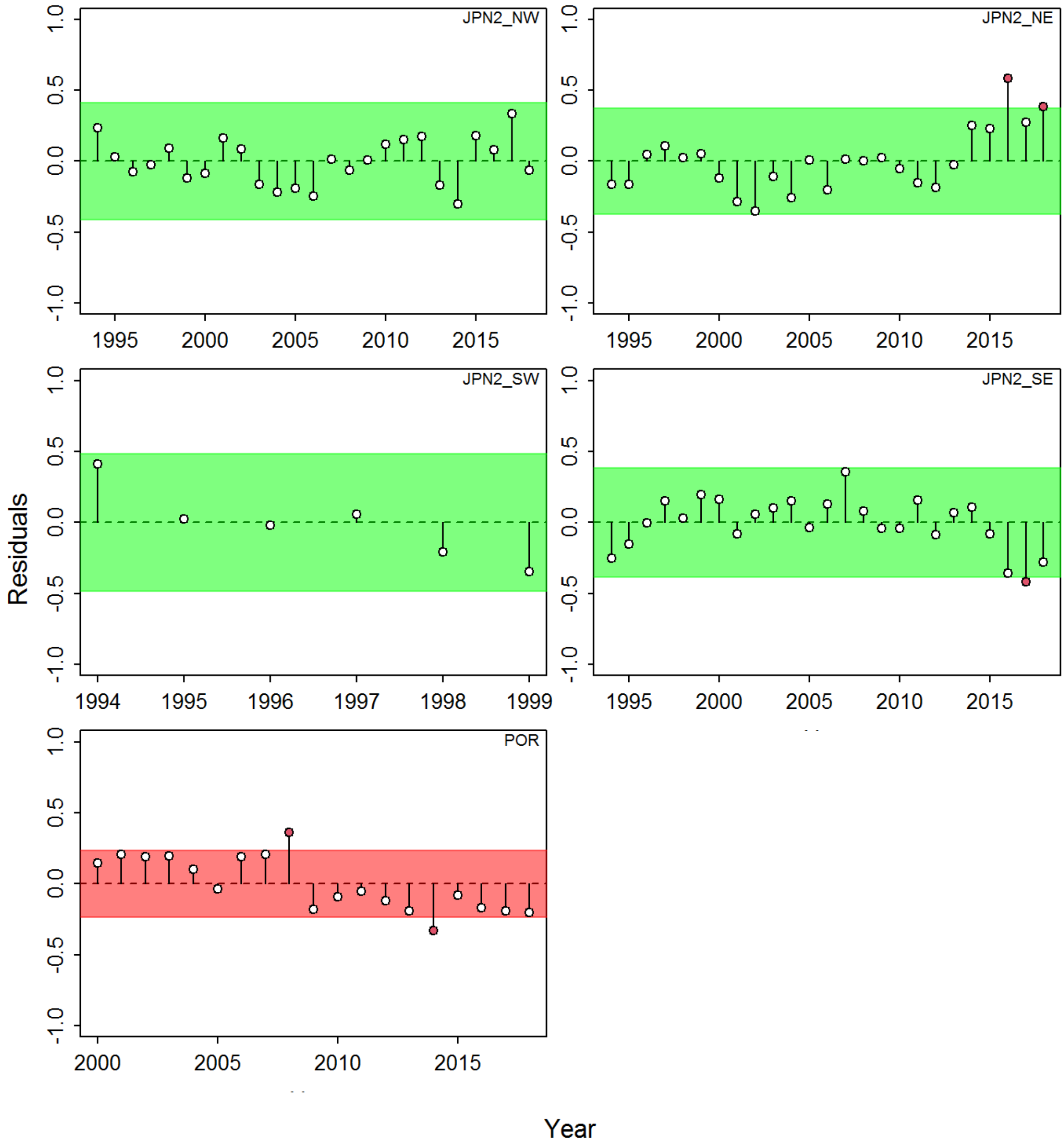


Figure 4 - Runs tests to quantitatively evaluate the randomness of the time series of CPUE residuals by fleet for the Reference Model. Green panels indicate no evidence of lack of randomness of time series residuals (p>0.05) while red panels indicate the opposite. The inner shaded area shows three standard errors from the overall mean and red circles identify a specific year with residuals greater than this threshold value (3x sigma rule).

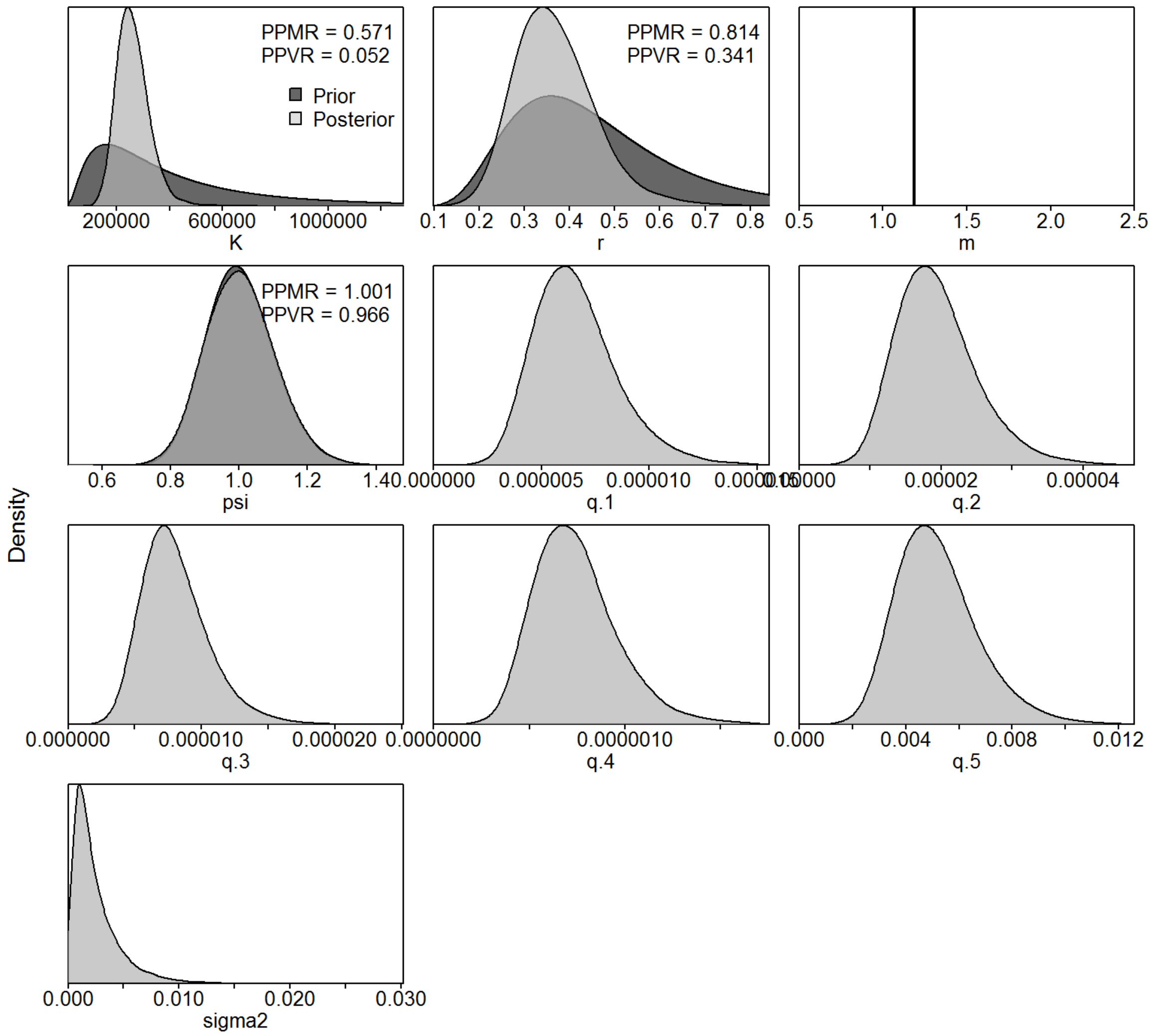


Figure 5 - Prior and posterior distributions of the Reference Model for the Bayesian state-space surplus production model Indian Ocean swordfish. PPRM: Posterior to Prior Ratio of Means; PPRV: Posterior to Prior Ratio of Variances.

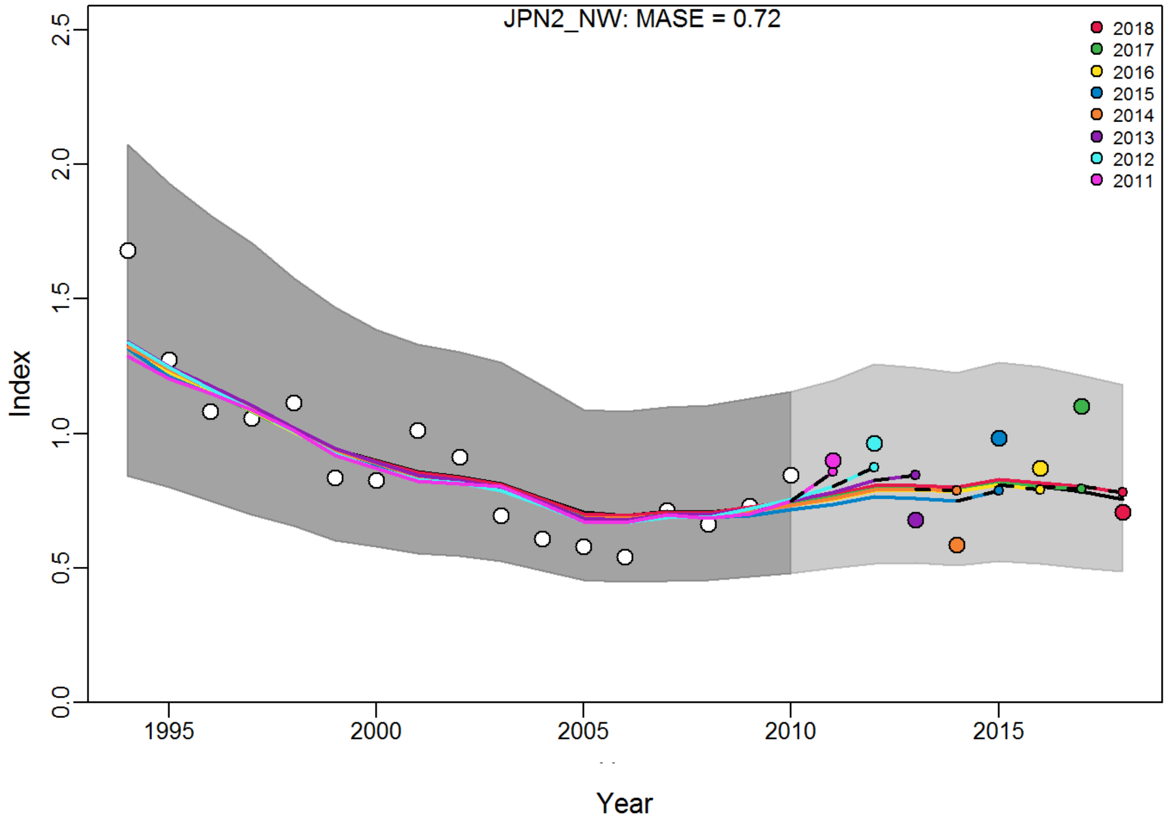


Figure 6 - Hindcasting cross-validation results (HCxval) for the Reference Model for Indian Ocean swordfish, showing one-year-ahead forecasts of CPUE values (2010-2018), performed with eight hindcast model runs relative to the expected CPUE. The CPUE observations, used for cross-validation, are highlighted as color-coded solid circles with associated light-grey shaded 95% confidence interval. The model reference year refers to the end points of each one-year-ahead forecast and the corresponding observation (i.e. year of peel + 1).

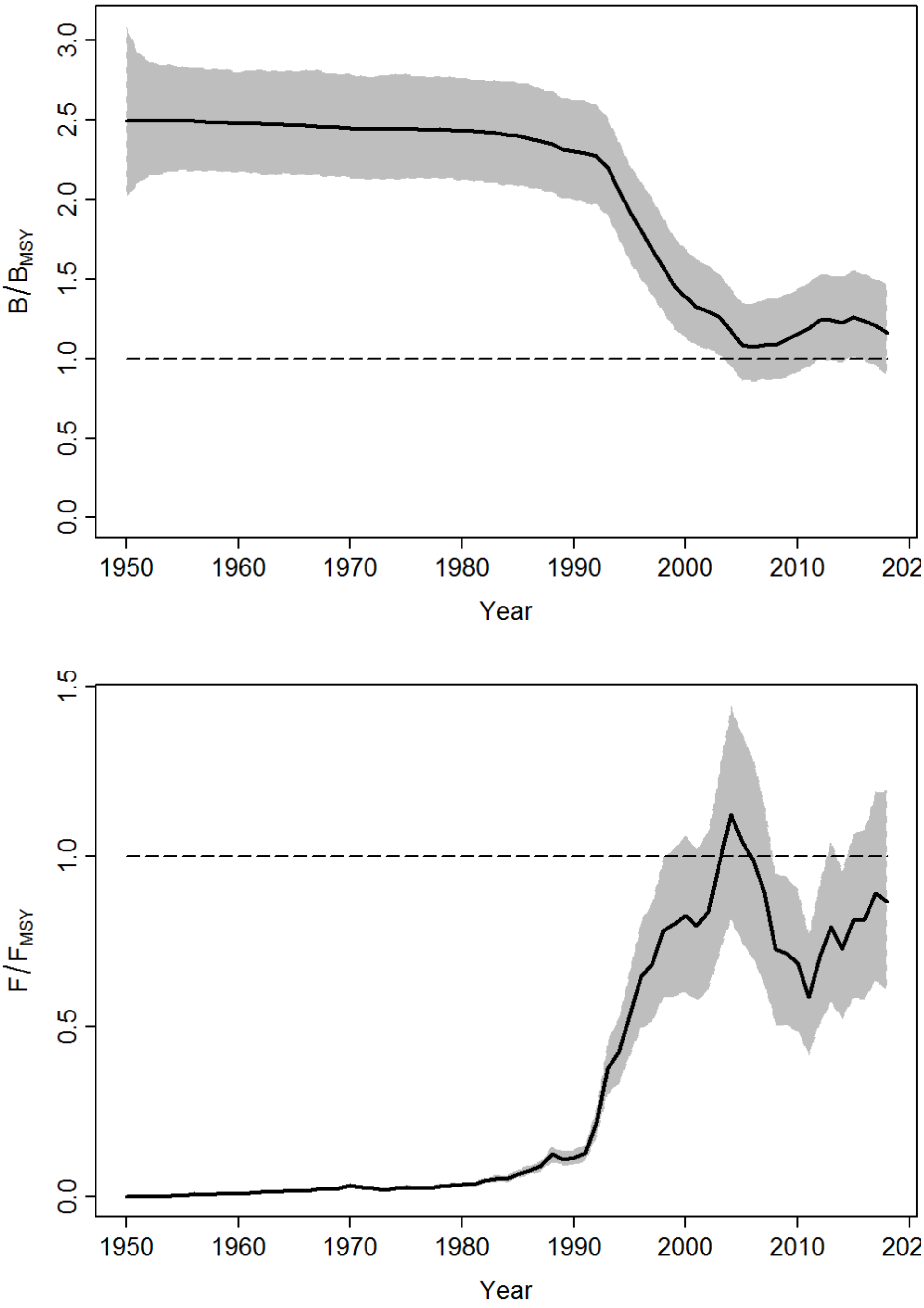


Figure 7 - Predicted trajectories of *B/B_{MSY}* (top panel) and *F/F_{MSY}* (bottom panel) for the Reference Model scenario of the Indian Ocean swordfish assessment. Grey shaded areas denote 95% CIs.

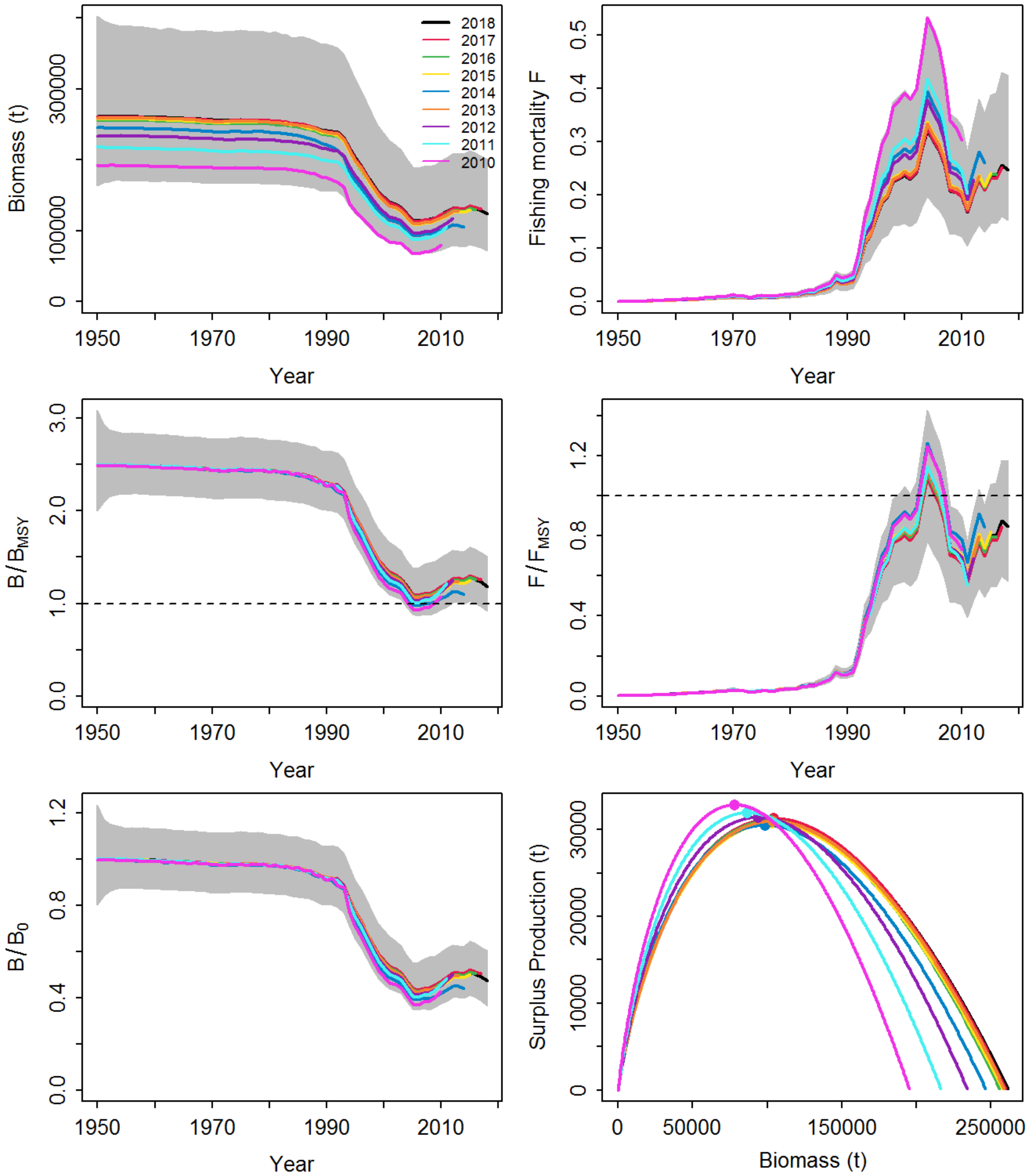


Figure 8 - Retrospective analysis performed on the Reference Model, by removing one year at a time sequentially (n=8) and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to B_{MSY} (B/B_{MSY}) and fishing mortality relative to F_{MSY} (F/F_{MSY}) (middle panels) and biomass relative to K (B/K) and surplus production curve (bottom panels) for each scenario from the model fits to the Indian Ocean swordfish.

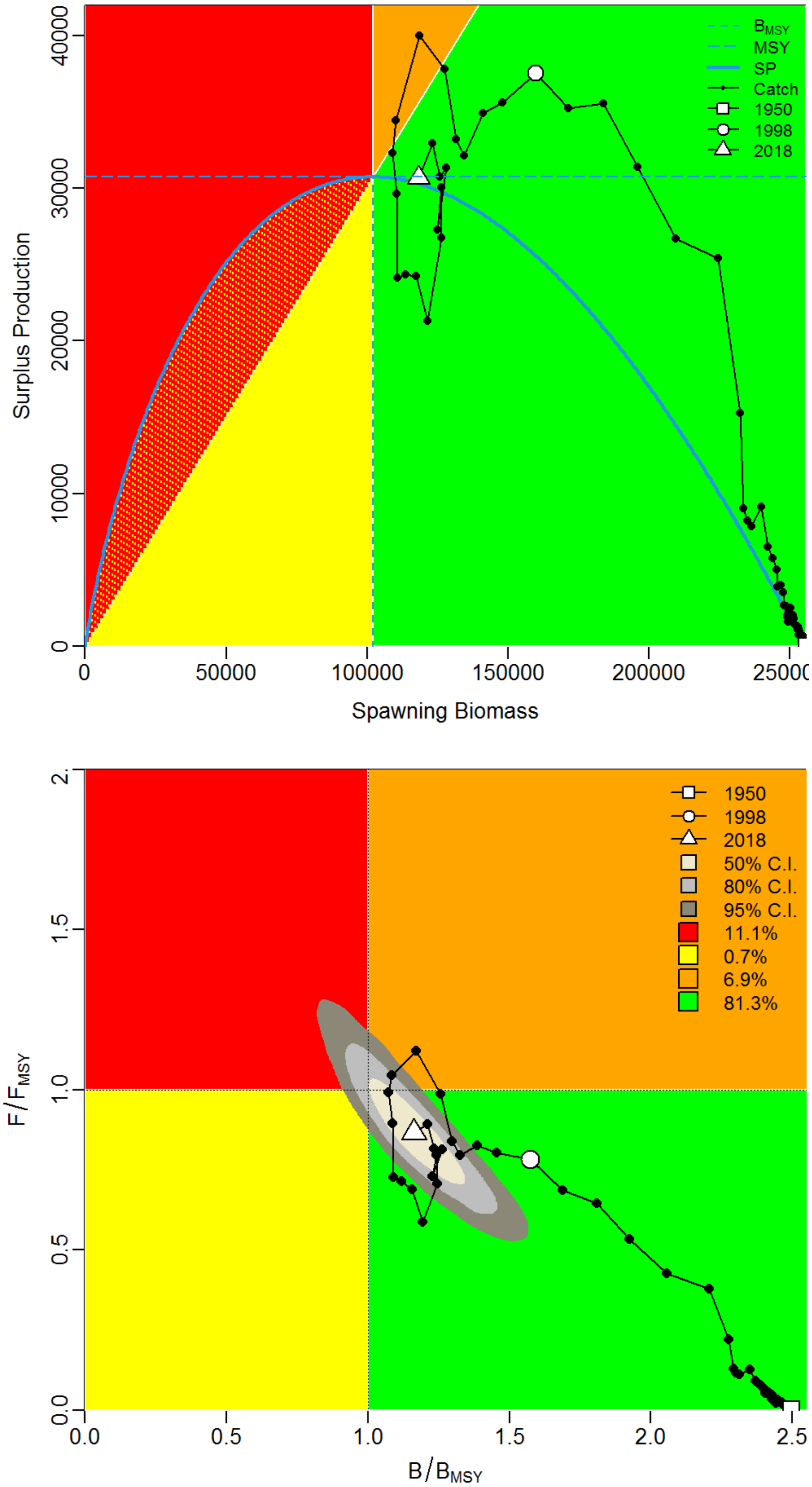


Figure 9 - JABBA surplus production phase plot for the Reference Model showing trajectories of the catches in relation to B_{MSY} and *MSY* (top panel) and Kobe phase plot showing estimated trajectories (1950-2018) of B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model for the Indian Ocean swordfish (bottom panel). Different grey shaded areas denote the 50%, 80%, and 95% credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

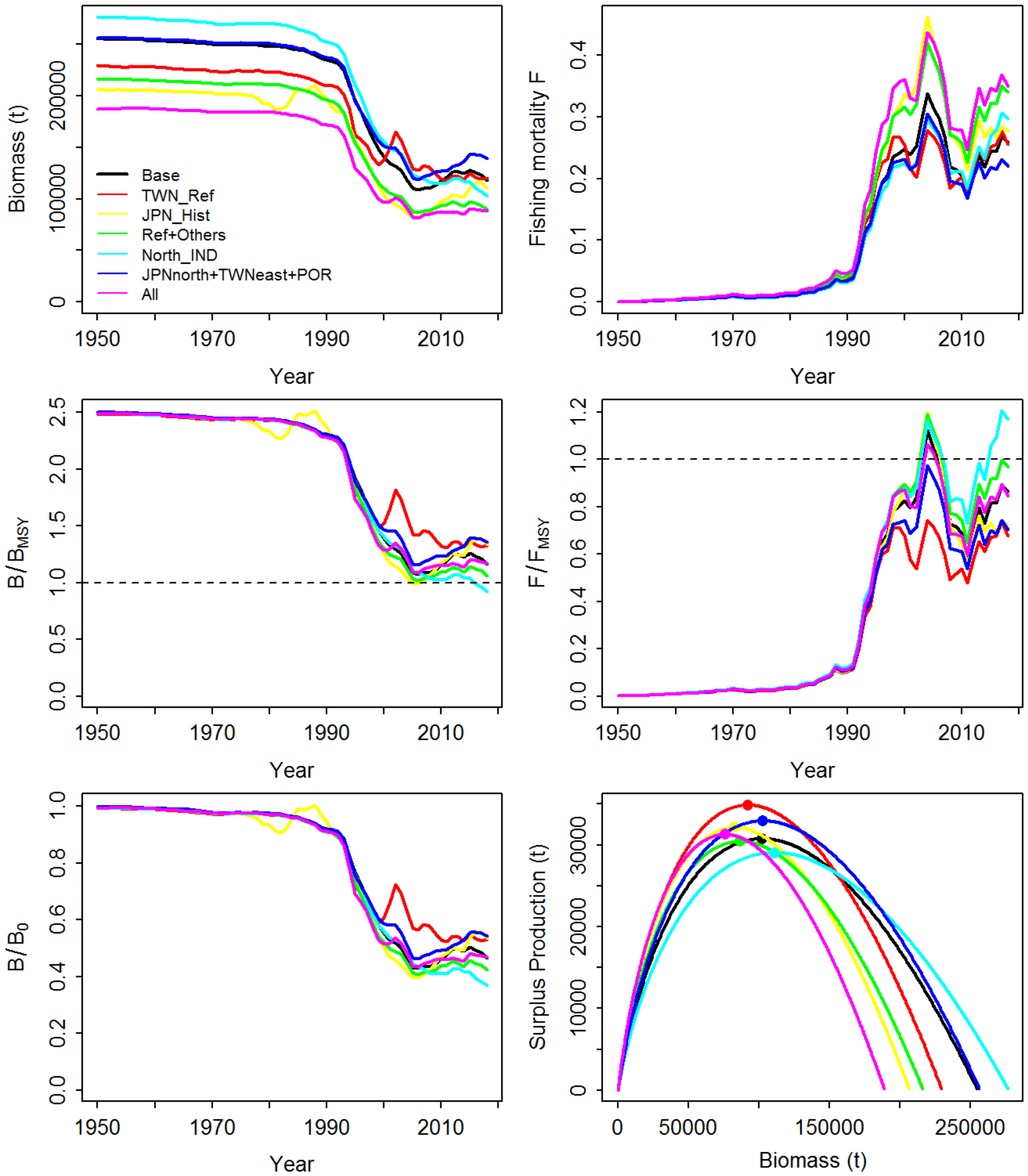


Figure 10 - Sensitivity analysis showing the influence of various CPUE scenarios on predicted stock biomass (*B*), fishing mortality (*F*), proportion of pristine biomass (*B/K*), surplus production function (maximum = *MSY*) and the stock status trajectories F/F_{MSY} and B/B_{MSY} for the Reference Model (black) for swordfish in the Indian Ocean. The scenarios that were considered are described in **Table 1**.