# ASSESSMENT OF THE SOUTH ATLANTIC SWORDFISH (*XIPHIAS GLADIUS*) STOCK USING JABBA

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## *SUMMARY*

*JABBA Models were fitted to South Atlantic swordfish (*Xiphias gladius*) data. This document presents details on the model diagnostics and stock status estimates for three preliminary models (S1-S3). In general, our results suggest that all candidate models are stable and provide robust fits to the data as judged by the presented model diagnostic results. Differences were observed in MSY with the S1 estimate being larger (13,224 t) than S2 and S3, which themselves were alike (11,849 and 11,723 t, respectively). Similarly, differences in biomass trends and fishing mortality between model S1 and models S2, S3 were obvious, with the S1 model indicating a more productive stock. However, when observed relative to MSY (i.e., $B/B_{MSY}$ and $F/F_{MSY}$ over time), all three models have remarkably similar trends that depict a recovering stock. Estimates of 2020 values from the three models indicate that the stock is moving from the "recovery" yellow quadrant into the green quadrant of the Kobe biplot ($B_{2020}/B_{MSY}$: 0.98 – 1.03; $F_{2020}/F_{MSY}$:0.68-0.79).*

## *RÉSUMÉ*

*Les modèles JABBA ont été ajustés aux données de l'espadon de l'Atlantique Sud (*Xiphias gladius*). Ce document présente les détails des diagnostics de modèles et des estimations de l'état des stocks pour trois modèles préliminaires (S1-S3). En général, nos résultats suggèrent que tous les modèles potentiels sont stables et fournissent des ajustements robustes aux données, comme en témoignent les résultats des diagnostics de modèles présentés. Des différences ont été observées dans la PME, l'estimation de S1 étant plus importante (13.224 t) que celles de S2 et S3, qui étaient elles-mêmes similaires (11.849 et 11.723 t, respectivement). De même, les différences dans les tendances de la biomasse et la mortalité par pêche entre le modèle S1 et les modèles S2 et S3 étaient évidentes, le modèle S1 indiquant un stock plus productif. Cependant, lorsqu'ils sont observés par rapport à la PME (c.-à-d. $B_{PME}$ et $F_{PME}$ au fil du temps), les trois modèles présentent des tendances remarquablement similaires qui représentent un stock en voie de rétablissement. Les valeurs estimées pour 2020 par les trois modèles indiquent que le stock passe du quadrant jaune « rétablissement » au quadrant vert du diagramme de double projection de Kobe ($B_{2020}/B_{PME}$ 0,98 – 1,03 ; $F_{2020}/F_{PME}$ :0,68- 0,79).*

## *RESUMEN*

*Los modelos JABBA se ajustaron a los datos del pez espada del Atlántico sur (*Xiphias gladius*). Este documento presenta detalles sobre los diagnósticos del modelo y las estimaciones del estado del stock para tres modelos preliminares (S1-S3). En general, nuestros resultados sugieren que todos los modelos candidatos son estables y proporcionan ajustes robustos a los datos según los resultados de diagnóstico del modelo presentados. Se observaron diferencias en el RMS, siendo la estimación de S1 mayor (13.224 t) que la de S2 y S3, que a su vez eran iguales (11.849 y 11.723 t, respectivamente). Asimismo, las diferencias en las tendencias de la biomasa y la mortalidad por pesca entre el modelo S1 y los modelos S2 y S3 eran evidentes, y el modelo S1 indicaba un stock más productivo. Sin embargo, cuando se observan en relación con el RMS (es decir, $B/B_{RMS}$ y $F/F_{RMS}$ a lo largo del tiempo), los tres modelos presentan tendencias notablemente similares que describen un stock en recuperación. Las estimaciones de los valores para 2020 de los tres*


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*modelos indican que el stock está pasando del cuadrante amarillo de "recuperación" al cuadrante verde del diagrama de Kobe (B2020/$B_{RMS}$: 0.98 – 1.03; F2020/$F_{RMS}$:0,68- 0,79).*

*KEYWORDS*

*Abundance, Stock assessment, Longlining,*
*Catch statistics, South Atlantic, stock status, CPUE fits, biomass model*

## 1. Introduction

Swordfish (*Xiphias gladius*) is the most widely distributed billfish species. The International Commission for the Conservation of Atlantic Tunas (ICCAT) considers there to be three stocks of swordfish in the Atlantic Ocean: North Atlantic (NA), South Atlantic (SA) and the Mediterranean Sea. Both conventional tagging (ICCAT, 2007) and pop-up satellite tags (Neilson et al., 2013) indicate a low probability of migration between the North and South Atlantic stocks units. The available catch histories of the three stocks are broadly comparable in terms of magnitude and trends, except prior 1980's in the North Atlantic, where the development of large swordfish directed longline fisheries by the USA, Canada, Portugal and Spain resulted in an earlier increase in catches than in the other regions (ICCAT, 2017a, 2017b).

The previous ICCAT SA swordfish stock assessment was run in 2017. That assessment comprised of two different Bayesian Surplus Production Models (SPMs), BSP2 and JABBA, both of which produced similar results in that stock biomass was overfished, and that overfishing was either occurring or that F was very close to $F_{MSY}$. Specifically, the assessment projections indicated that the observed catch levels (10,058 t) would likely rebuild the stock to achieve reach the green quadrant of the Kobe plot by 2020, whereas catches of 13,000 t would result in a 60% probability of the stock reaching the green quadrant by 2024. There, the 2017 assessment proposed that the TAC should not exceed 13,000 t.

During the 2017 SA swordfish assessment much focus was given to identifying and resolving potential CPUE data conflicts that may arise from fitting of multiple standardized CPUE time series. The base-case CPUE data therefore excluded the historical Brazil series and split the Japanese CPUE at 2005/2006, and the EU-Spain series was split at 1999/2000. In March 2022, a data preparatory meeting was held to evaluate swordfish input data for the upcoming assessment. While much progress was made with respect to swordfish CPUE indices for the South Atlantic to overcome the challenges faced in the 2017 assessment, it was clear that time-blocks were still required for certain fleets.

Biological research on the SA swordfish stock is more limited than the North (Neilson *et al.* 2013), for reasons such as the lack of an ICCAT research programs in these areas as well as the shorter historical fishery activity and countries involved (Quelle et al., 2013). In biomass aggregated models, such as SPMs, somatic growth, reproduction, natural mortality, and associated density-dependent processes are inseparably captured in the estimated surplus production function. Therefore, structural, and biological uncertainty is typical represented in the form of alternative values of $r$ and the shape $m$ of the production function. In the 2017 SA swordfish assessment, a single $r$ prior (mean= log(0.42), sd = 0.37) was assumed for all models, which was the same as in the 2013 assessment (McAllister, 2014). Given the importance of the surplus production function, it was noted in the data preparatory meeting that input priors related to the production function should be objectively derived from the simulations in an Age Structured Equilibrium Model (ASEM).

Here we present stock assessment results for SA 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 for the period 1950-2020. JABBA is a fully documented, open-source R package (www.github.com/JABBAmodel) that has been formally included in the ICCAT stock catalogue (https://github.com/ICCAT/software/wiki/2.8-JABBA) and management advice for the 2017 SA swordfish assessment was derived from the JABBA model results (ICCAT, 2017).

## 2. Material and Methods

### 2.1. *Fishery data*

Total catch of SA swordfish from 1950-2020 were obtained from the analysis carried out during the data preparatory meeting in March 2022 (ICCAT, 2022) and includes reported landings and dead discards (**Figure 1**). Indices of relative abundance were made available in the form of standardized catch-per-unit-of-effort (CPUE) time series, which were assumed to be proportional to biomass. Standardized CPUE series were obtained from several major fishing fleets operating in the South Atlantic Ocean, all of which were longline (LL). For this assessment 6 standardized CPUE series were made available: Brazil, EU-Spain, Japan, Uruguay, Chinese Taipei and South Africa (**Figure 3**). The Japan and Chinese Taipei indices were split into two separate time blocks as discussed in the data preparatory meeting (ICCAT, 2022), while EU-Spain was split into two separate time blocks for continuity with the 2017 assessment.

- Brazil longlines (1994-2020)
- EU-Spanish longlines (1989-1999; 2000-2019)
- Japan longlines (1976-1993; 1994-2020)
- Uruguay longlines (2001-2012)
- Chinese Taipei longlines (1968-1990; 1998-2020)
- South Africa longlines (2004-2020)

### 2.2. *JABBA stock assessment model fitting procedures*

This stock assessment uses the most updated version (v2.2.4) of JABBA and can be found online at: https://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 shape a parameter $m$.

For the unfished equilibrium biomass $K$, we used default settings of the JABBA R package in the form of vaguely informative lognormal prior with a large CV of 100% and a central value that corresponds to eight times the maximum total catch and is consistent with other platforms such as Catch-MSY (Martell and Froese, 2013) or SpiCt (Pederson and Berg 2017). Initial depletion was input as a "beta" prior ($\varphi = B_{1950}/K$) with mean = 0.95 and CV of 5%. This distribution is considered more appropriate than a lognormal for initial depletion, given the understanding that there was very little fishing before the starting year of 1950. All catchability parameters were formulated as uninformative uniform priors, while additional observation variances were estimated for index by assuming inverse-gamma priors to enable model internal variance weighting. Instead, 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. Observation error for CPUE estimates were fixed at 0.25.

Initial trials considered three alternative specifications of the Pella-Tomlinson model type based on different sets of $r$ priors and fixed input values of $B_{MSY}/K$. The input $r$ prior for S1 are identical to those used in the previous two assessments (Winker et al., 2017; McAllister, 2014). The input $r$ priors for S2 and S3 were objectively derived from age-structured model simulations (see details in Winker et al. 2019 and Winker et al., 2018b), based on two different growth models for SA swordfish provided by Garcia et al. (2016) and Quelle et al. (2014), respectively, as well as other biological parameters (**Tables 1** and **2**). This allowed us to approximate the parameterizations considered for the Stock Synthesis model based on range of stock recruitment steepness values for the stock-recruitment relationship ($h$ = 0.6, $h$ = 0.7 and $h$ = 0.8), while admitting reasonable uncertainty about the natural mortality $M$ (CV of 30% and the central value mean value of 0.2). Based on sensitivity analysis of the initial runs of S2 and S3, including the three 'steepness-specific' $r$ input priors (results not shown here), a corresponding steepness of $h$ = 0.7 was selected. This translates to an associated lognormal $r$ prior of $\log(r) \sim N(\log(0.155),0.117)$ and a fixed input value of $B_{MSY}/K$ = 0.38 for S2, and a lognormal $r$ prior of $\log(r) \sim N(\log(0.138),0.1)$ and a fixed input value of $B_{MSY}/K$ = 0.37 for S3 (**Table 3**).

**S1 (Continuity):** $\log(r) \sim N(\log(0.42),0.37)$; $B_{MSY}/K$ = 0.4; all CPUE

**S2 (Garcia):** $\log(r) \sim N(\log(0.155),0.117)$; $B_{MSY}/K$ = 0.38; all CPUE

**S3 (Quelle):** log($r$) ~ $N(\log(0.138),0.1)$; $B_{MSY}/K$ = 0.37; all CPUE

### 2.3. *Model diagnostics*

The evaluation model diagnostics follows the principles in Carvalho et al. (2021), who recommended to objectively evaluate the base-case candidate model based on the following four model plausible criteria: (1) model convergence (2) fit to the data, (3) model consistency (retrospective pattern) and (4) prediction skill through hindcast cross-validation (Kell et al. 2016; 2021).

JABBA is implemented in R (R Development Core Team, https://www.r-project.org/) with 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. 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 the JABBA fit to the abundance index data, the model predicted values were compared to the observed indices. Residual plots were used to examine (1) color-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. We conducted run tests to evaluate the randomness of residuals (Carvalho et al., 2017). The runs 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 1- sided p-value of the Wald-Wolfowitz runs test (Carvalho et al. 2021).

To check for model consistency with respect to the stock status estimates, we also performed a retrospective analysis on S2 by removing one year of data at a time sequentially (n = 5), 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 S2 model that is fitted to full time series. To compare the bias between the models, we computed Mohn's (Mohn, 1999) rho ($\rho$) statistic and specifically the commonly used formulation Hurtado-Ferro et al. (2015).

To validate a model's prediction skill, we applied a hindcasting cross-validation (HCXval) technique (Kell et al. 2016), where observations are compared to their predicted future values. HCxval is a form of cross-validation where, like retrospective analysis, recent data are removed, and the model refitted with the remaining data, but HCXval involves the additional steps of projecting ahead over the missing years and then cross-validating these forecasts against observations to assess the model's prediction skill. A robust statistic for evaluating prediction skill is the Mean Absolute Scaled Error (MASE), which scales the mean absolute error of prediction residuals to a naïve baseline prediction, where a 'prediction' is said to have 'skill' if it improves the model forecast when compared to the naïve baseline (Kell et al. 2021). The MASE score scales the mean absolute error of the prediction residuals to the mean absolute error of a naïve in-sample prediction and a score of higher than one can be interpreted such that the average model forecasts are no better than a random walk. Conversely, a MASE score of 0.5 indicates that the model forecasts twice as accurately as a naïve baseline prediction; thus, the model has prediction skill.

## 3. Results and Discussion

The MCMC convergence tests by Heidelberger and Welch (Heidelberger and Welch, 1992) and Geweke (1992) and Gelman and Rubin (1992), as well as visual inspection of trace plots, indicate adequate convergence in all models. Furthermore, identical models run produce consistent results, indicating a good level of model stability.

The S2 model fit to each of the nine (six fleets, three of which had split time series) standardized CPUE LL indices are shown in **Figure 3.** The S2 model appeared to fit CPUE data reasonably well, and the goodness-of-fit was estimated to be RMSE = 21% (**Figure 2**). The residual patterns in the beginning of the time series are driven by the CPT1 index, which is the main "historical" index. There is some conflict in the last five years (2015-2020) between the JPN2 index and the other indices, with the former producing increasingly positive residuals that contrast the negative residual trend for the period observed in the BRA, CTP2 and ZAF indices. As such, the JPN2

index is highly influential. Furthermore, given an overall decrease in landings since the mid 1990's as well as observed negative CPUE trends in recent years (BRA, CTP2 and ZAF) the estimated process error deviates show a negative trend for the period 1950-2020 in all three models (**Figure 5**). Thus, the model interprets the stock's productivity as having been below average in recent years.

Run tests conducted on the log-residuals indicated that the CPUE residuals may not be randomly distributed for five of the nine indices: BRA, EU-SPN1, EU-SPN2, JPN2, CTP1 and CTP2 (**Figure 4**). This suggests data-conflicts caused by the opposite trends when compared to the other CPUE time series, as well as the presence of outliers. The CPUE fits for S1 and S3 (not shown) were comparable.

Marginal posterior distributions along with prior densities for all three models are shown in **Figures 6,7** and **8**. The prior to posterior median ratio (PPMR) for *r* in models S2 and S3 were close to 1, indicating that the posterior is heavily influenced by the prior. This was expected, given the low CVs that were estimated in the development of the priors (**Table 3**). In contrast, the relatively small prior to posterior variance ratio (PPVR) of *r* for S1 can be ascribed to the larger CV, but also indicates that the input data are to some extent informative about *r*. Similarly, the resulting small PPVRs observed in S2 and S3 *K* indicate that the input data was more informative about *K* for these two models that for S1. The marginal posteriors for initial depletion ($\varphi$) were similar between all three models, with both PPMR and PPVR close to 1, which suggests that this parameter was largely informed by the priors.

Summaries of posterior quantiles for parameters and management quantities of interest are presented in **Table 4** Estimates of *MSY* were very similar between models S2 and S3 (11,849 and 11,723 t, respectively), while the *MSY* estimate for S1 was larger (13,224 t). The marginal posterior median for $B_{MSY}$ varied between 47,993 metric tons (S1) and 81,905 metric tons (S3). The $F_{MSY}$ median estimate for S1 (0.278) was substantially higher than models S2 and S3 (0.155 and 0.143, respectively) (**Table 4)**. Similarly, differences are observed between model S1 and models S2, S3 in the trends in biomass and fishing mortality (**Figure 9**), with the S1 model indicating a more productive stock that that modelled in S2 and S3. This manifest clearly in estimates of *K*, whereby S1 (119,988 t) is almost double that of S3 (221,321 t). However, when observed relative to *MSY* (i.e., $B/B_{\mathrm{MSY}}$ and $F/F_{\mathrm{MSY}}$ over time) all models have very similar trends (**Figure 9**). The trajectory of $B/B_{MSY}$ showed an overall decreasing trend from 1970 to around 2000, thereafter the decreasing trend stabilized somewhat and has fluctuated around $B/B_{MSY}$ = 1 until 2020. The lowest level of $B/B_{MSY}$ was observed in 2011. The $F/F_{MSY}$ trajectory showed a gradual increasing trend between 1970 and the mid-1980s, and a sharp increase in the late-1980s to peak in 1995. After 1995, $F/F_{MSY}$ steadily decreased (**Figure 9**). Current estimates of $F/F_{MSY}$ are well below 1 (range: 0.675 (S1) - 0.786 (S2)).

A retrospective analysis for five years was run on S2 and the results presented in **Figure 10,** which shows minimal retrospective deviations from the full model. Furthermore, **Table 5** depicts the Mohn's rho statistic computed for a retrospective evaluation period of five years. The estimated Mohn's rho for *B* and $B/B_{MSY}$ fell within the acceptable range of -0.15 and 0.20 (Hurtado-Ferro et al. 2014; Carvalho et al. 2017) and consequently indicated that the retrospective pattern for model S2 was negligible. Retrospective results are similar for S1 and S3 (not shown here).

The Jackknife sensitivity analysis of CPUE indices performed on model S2 showed that the Chinese-Taipei early (CPT1) and Japanese late (JPN2) are highly influential with regards to stock status trajectories and MSY (**Figure 11**). Removing the CPT1 index resulted in much more optimistic stock status trajectories, with biomass level well above $B_{MSY}$. This is likely due to the CPT1 index being the oldest (1968-1990), and the model therefore relies heavily on this index to describe the initial decline due to fishing. In contrast, removing the JPN2 index would result in considerably more pessimistic stock trajectories and produces the only scenario whereby the terminal biomass levels fall well below $B_{MSY}$. This is due to the significant increase in the Japanese CPUE trend since 2015.

Kobe biplots for all three models are shown in **Figure 12**. A typical anti-clockwise pattern is present, with the stock status moving from underexploited through a period of unsustainable fishing to the overexploited phase and then to the recovery phase after a decrease in fishing mortality. Currently, all three models indicate that the stock is moving from the "recovery" yellow quadrant into the green quadrant of the Kobe biplot. The resultant stock status posteriors for 2020 from each model have the highest probability falling within the green quadrant (45% - 55.7%). Furthermore, the probability that current fishing mortality is sufficiently low enough to facilitate stock rebuilding (yellow + green) is cumulatively above 85% in each model.

Our results suggest that all three candidate models are stable and provide reasonably robust fits to the data as judged by the presented model diagnostic results. There is no evidence to favor any of the three models based on performance alone. There is a notable difference in estimated productivity between model S1 (the continuity run

from 2013 and 2017 assessments) and models S2, S3, with the former assuming a more productive stock. However, when assessed relative to *MSY* there is remarkable consistency between the three models. Furthermore, continuity exists between the results from the 2017 assessment and the current results. The 2017 assessment projections indicated that if catches remained below 11,000 t, there was a 60% chance of the stock falling within the green quadrant by 2020. The average catch of SA swordfish for the period 2016-2020 is 10,125 and the estimated probability of falling within the green quadrant from this assessment ranges between 45 - 55.7%. Given the continuity model (S1) assumes a more productive stock, these results seem plausible.

The final Reference case scenario that was decided on at the SWO meeting is provided in Appendix 1.

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**Table 1.** Life history parameters used to estimate *r* prior distributions and median shape parameter with corresponding $B_{MSY}/K$ values for S2 (Garcia et al. growth model) of the for South Atlantic swordfish assessment. The priors are generated using an Age-Structured Equilibrium Model (ASEM).

| Parameter | Mean | CV | Distribution | Description | Source |
|---|---|---|---|---|---|
| *M* | 0.2 | 0.35 | Lognormal | Natural Mortality (1/year) | - |
| $L_{inf}$ (cm) female | 307.86 | 0.1 | Lognormal | Von Bertalanffy asymptotic length | Garcia *et al.* (2016) |
| $L_{inf}$ (cm) male | 238.91 | | | | |
| *K* female | 0.093 | 0.1 | Normal | Von Bertalanffy growth parameter | Garcia *et al.* (2016) |
| *K* male | 0.145 | | | | |
| $t_o$ female | -2.246 | 0.2 | Normal | Von Bertalanffy age at zero length | Garcia et al. (2016) |
| $t_o$ male | -1.736 | | | | |
| *A* female | 1.69E-06 | - | Exponential | Weight at length parameter (GG-LJFL) | SCRS/2017/079 Forselledo et al.(2017) |
| *A* male | 4.61E-06 | | | | |
| *B* female | 3.32 | - | Exponential | Weight at length parameter (GG-LJFL) | SCRS/2017/079 Forselledo et al.(2017) |
| *B* male | 3.12 | | | | |
| $L_{50}$ (cm) female | 156 | 0.2 | Lognormal | Length at 50% maturity | Hazin et al. (2002) |
| $L_{50}$ (cm) male | 125 | | | | |
| *D* | $L_{50}$ x0.05 | 0.2 | Lognormal | Logistic maturity ogive | Knife-edge |
| $t_{max}$ (y) | 15 | 0.2 | Lognormal | Longevity | FishLife |
| $L_c$ (cm) | 119 | fixed | Fixed | Length at 50% selectivity | 25th percentile LF |
| *H* | 0.6-0.8 | fixed | Range | Steepness | - |

**Table 2.** Life history parameters used to estimate *r* prior distributions and median shape parameter with corresponding $B_{MSY}/K$ values for S3 (Quelle et al. growth model) of the for South Atlantic swordfish assessment. The priors are generated using an Age-Structured Equilibrium Model (ASEM).

| Parameter | Mean | CV | Distribution | Description | Source |
|---|---|---|---|---|---|
| *M* | 0.2 | 0.35 | Lognormal | Natural Mortality (1/year) | - |
| $L_{inf}$ (cm) | 358.7 | 0.1 | Lognormal | Von Bertalanffy asymptotic length | Quelle et al. (2014) |
| *K* | 0.092 | 0.1 | Normal | Von Bertalanffy growth parameter | Quelle et al. (2014) |
| $t_o$ | -1.929 | 0.2 | Normal | Von Bertalanffy age at zero length | Quelle et al. (2014) |
| *A* female | 1.69E-06 | - | Exponential | Weight at length parameter (GG-LJFL) | SCRS/2017/079 Forselledo et al.(2017) |
| *A* male | 4.61E-06 | | | | |
| *B* female | 3.32 | - | Exponential | Weight at length parameter (GG-LJFL) | SCRS/2017/079 Forselledo et al.(2017) |
| *B* male | 3.12 | | | | |
| $L_{50}$ (cm) female | 156 | 0.2 | Lognormal | Length at 50% maturity | Hazin et al. (2002) |
| $L_{50}$ (cm) male | 125 | | | | |
| *D* | $L_{50}$ x0.05 | 0.2 | Lognormal | Logistic maturity ogive | Knife-edge |
| $t_{max}$ (y) | 15 | 0.2 | Lognormal | Longevity | FishLife |
| $L_c$ (cm) | 119 | fixed | Fixed | Length at 50% selectivity | 25th percentile LF |
| *H* | 0.6-0.8 | fixed | Range | Steepness | - |

**Table 3.** Results for *r* prior distributions and median shape parameter with corresponding $B_{MSY}/K$ values generated an Age-Structured Equilibrium Model (ASEM).

| Parameter | Scenario | | |
|---|---|---|---|
| | **S1 (Continuity)** | **S2 (Garcia)** | **S3 (Quelle)** |
| *r* | 0.42 | 0.155 | 0.138 |
| sd of log(*r*) | 0.37 | 0.117 | 0.1 |
| $B_{MSY}/K$ | 0.4 | 0..38 | 0.37 |
| shape *m* | 2 | 1.05 | 1.03 |

**Table 4.** 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 models for South Atlantic swordfish.

| | **S1 (Continuity)** | | | **S2 (Garcia)** | | | **S3 (Quelle)** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Estimates** | ***Median*** | ***2.5%*** | ***97.5%*** | ***Median*** | ***2.5%*** | ***97.5%*** | ***Median*** | ***2.50%*** | ***97.50%*** |
| $K$ | 119 988 | 79 925 | 190 483 | 201 542 | 159 746 | 256 607 | 221 321 | 178 375 | 276 684 |
| $R$ | 0.330 | 0.194 | 0.517 | 0.165 | 0.133 | 0.205 | 0.144 | 0.119 | 0.174 |
| $\sigma_{proc}$ | 0.964 | 0.824 | 0.998 | 0.964 | 0.822 | 0.998 | 0.963 | 0.825 | 0.998 |
| $F_{MSY}$ | 0.278 | 0.164 | 0.435 | 0.155 | 0.125 | 0.192 | 0.143 | 0.119 | 0.173 |
| $B_{MSY}$ | 47 993 | 31 968 | 76 189 | 76 595 | 60 710 | 97 522 | 81 905 | 66 012 | 102 394 |
| $MSY$ | 13 224 | 11 335 | 16 415 | 11 849 | 9 962 | 14 104 | 11 723 | 9 808 | 14 013 |
| $B_{1950}/K$ | 0.952 | 0.758 | 1.151 | 0.956 | 0.784 | 1.112 | 0.954 | 0.791 | 1.102 |
| $B_{2020}/K$ | 0.41 | 0.268 | 0.611 | 0.372 | 0.249 | 0.531 | 0.38 | 0.254 | 0.525 |
| $B_{2020}/B_{MSY}$ | 1.025 | 0.67 | 1.529 | 0.979 | 0.655 | 1.397 | 1.027 | 0.686 | 1.418 |
| $F_{2020}/F_{MSY}$ | 0.675 | 0.377 | 1.071 | 0.786 | 0.49 | 1.214 | 0.756 | 0.485 | 1.193 |

**Table 5.** Summary of model S2 Mohn's rho statistic computed for a retrospective evaluation period of five years. The larger the threshold the stronger is the retrospective bias.

| | Stock Quantity | | | | |
|---|---|---|---|---|---|
| Model | *B* | *F* | $B/B_{MSY}$ | $F/F_{MSY}$ | MSY |
| S2 | -0.019 | 0.021 | -0.020 | 0.004 | 0.016 |

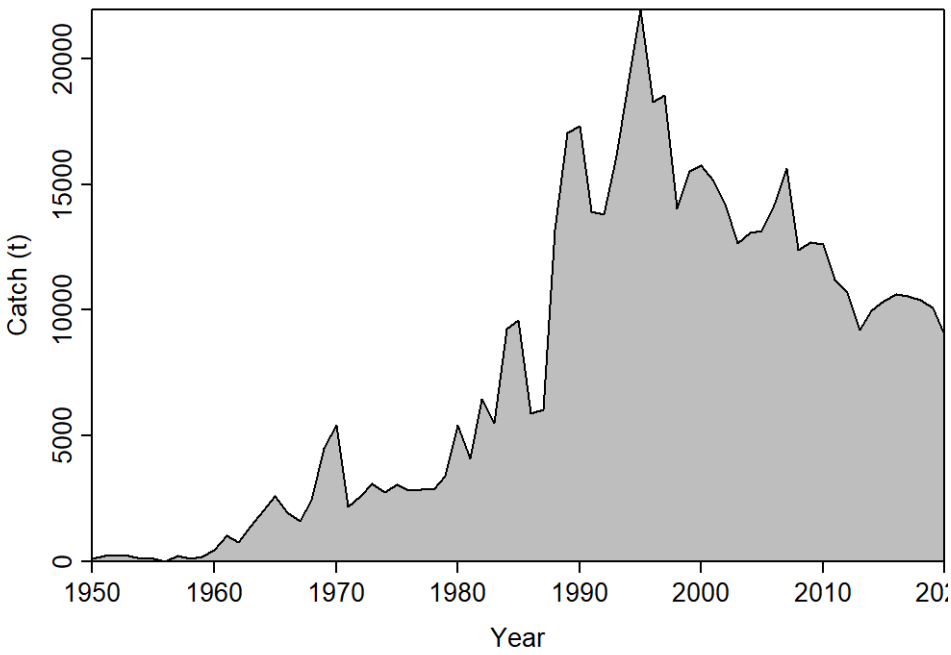


**Figure 1.** Available catch times series in metric tons (t) for South Atlantic swordfish for the period 1950 - 2020.

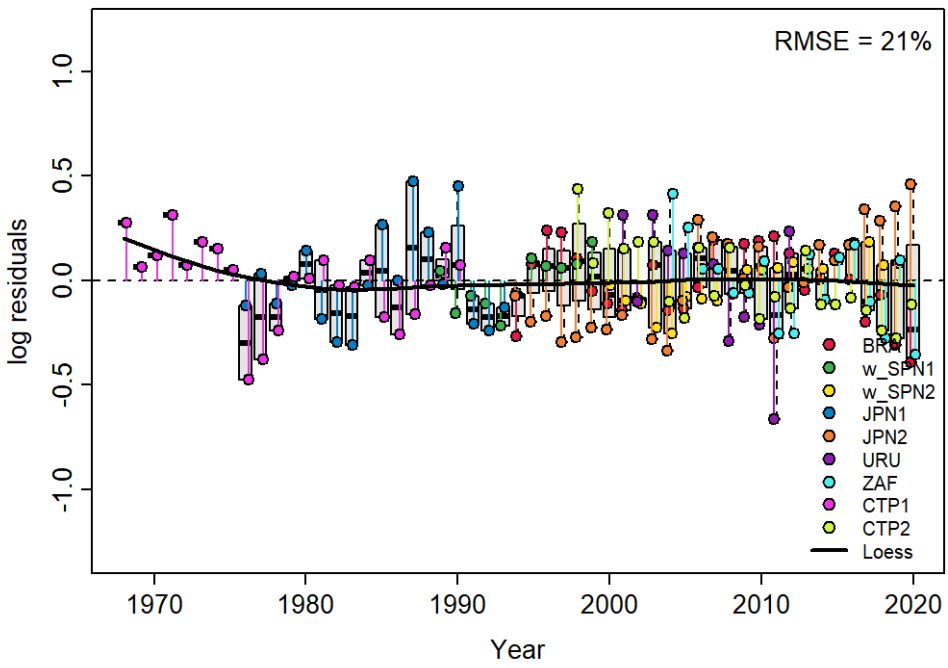


**Figure 2.** Residual diagnostic plots of CPUE indices for the South Atlantic swordfish model S2. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals.

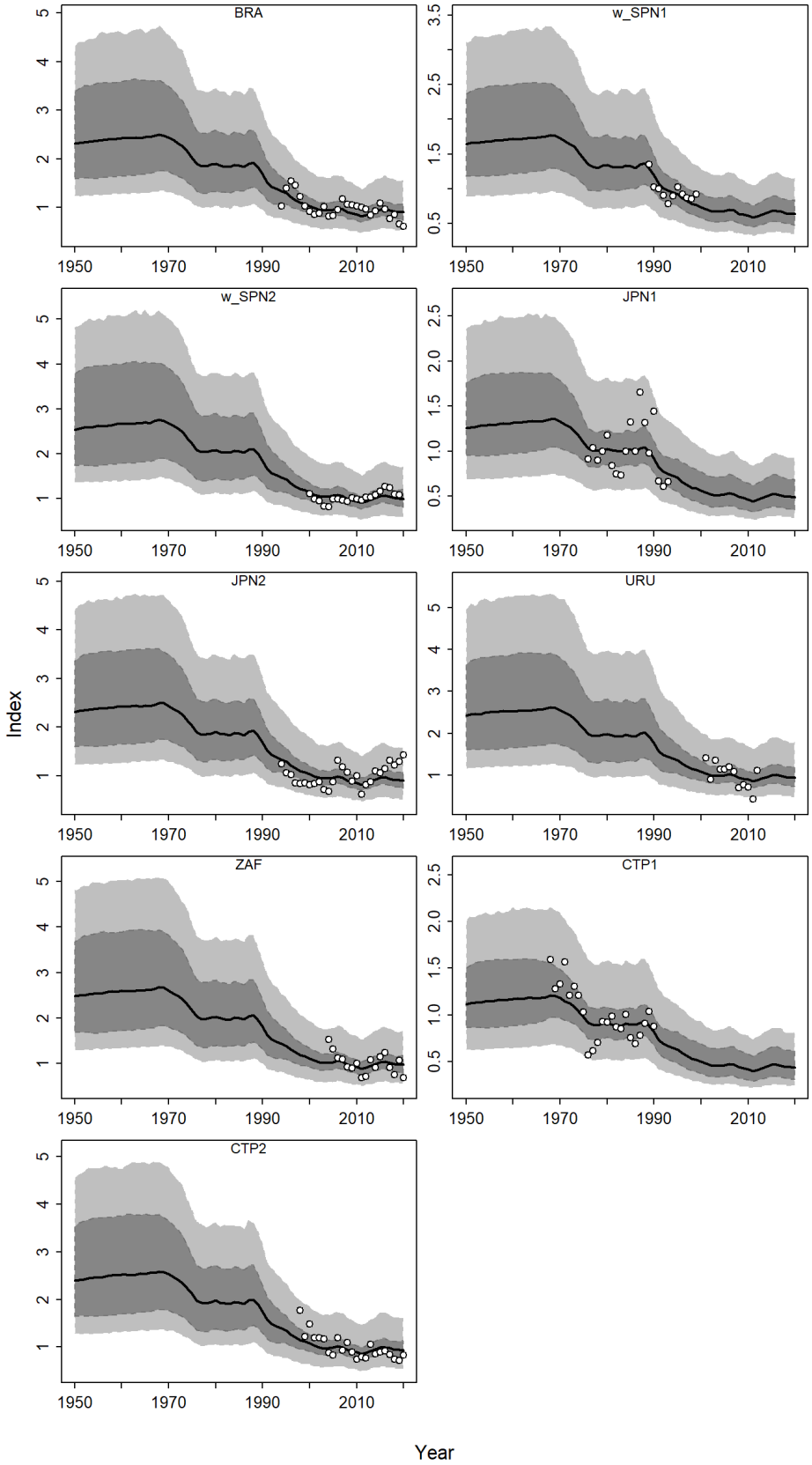


**Figure 3.** Time-series of observed (circle) and predicted (solid line) CPUE of South Atlantic swordfish for the JABBA model S2. The Dark shaded grey areas show 95% credibility intervals of the expected mean CPUE and light shaded grey area denote the 95% posterior predictive distribution intervals.

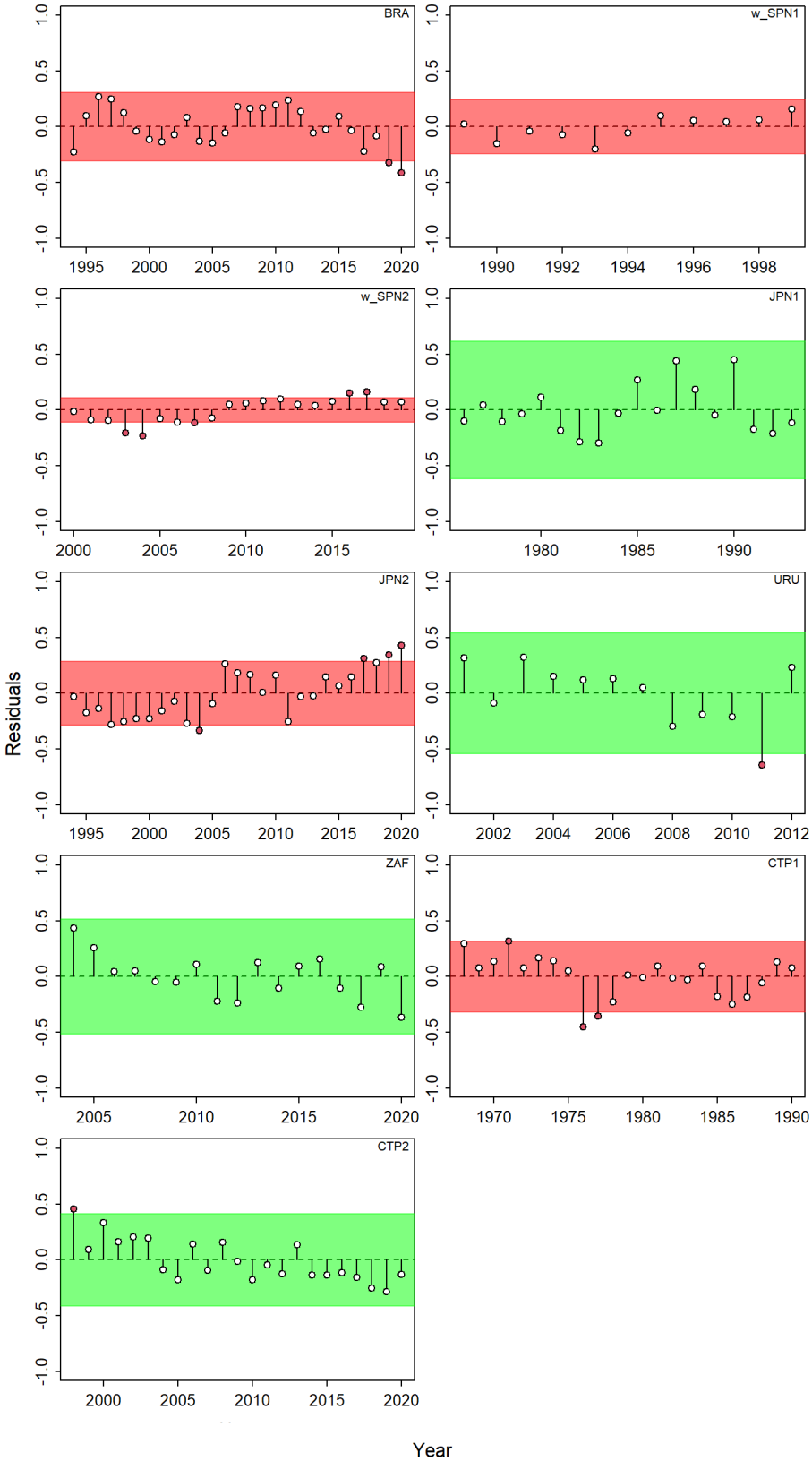


**Figure 4.** Runs tests to evaluate the randomness of the time series of CPUE residuals by fleet for S2. Green panels indicate no evidence of lack of randomness of time-series residuals ($p$>0.05) while red panels indicate possible autocorrelation. The inner shaded area shows three standard errors from the overall mean and red circles identify a specific year with residuals greater than this threshold value (3x sigma rule).

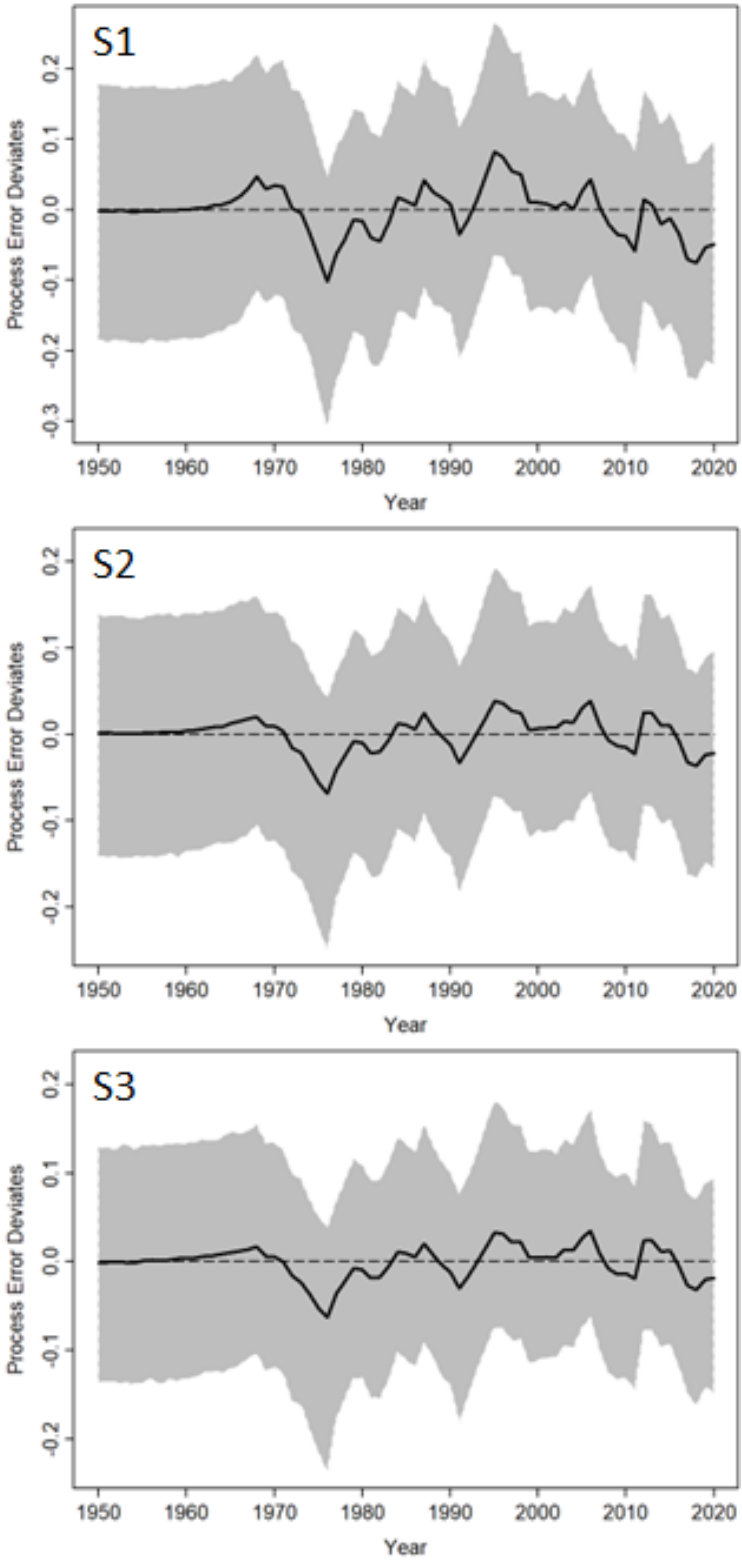


**Figure 5.** Process error deviates (median: solid line) of South Atlantic swordfish for each JABBA model (S1- S3). Shaded grey area indicates 95% credibility intervals.

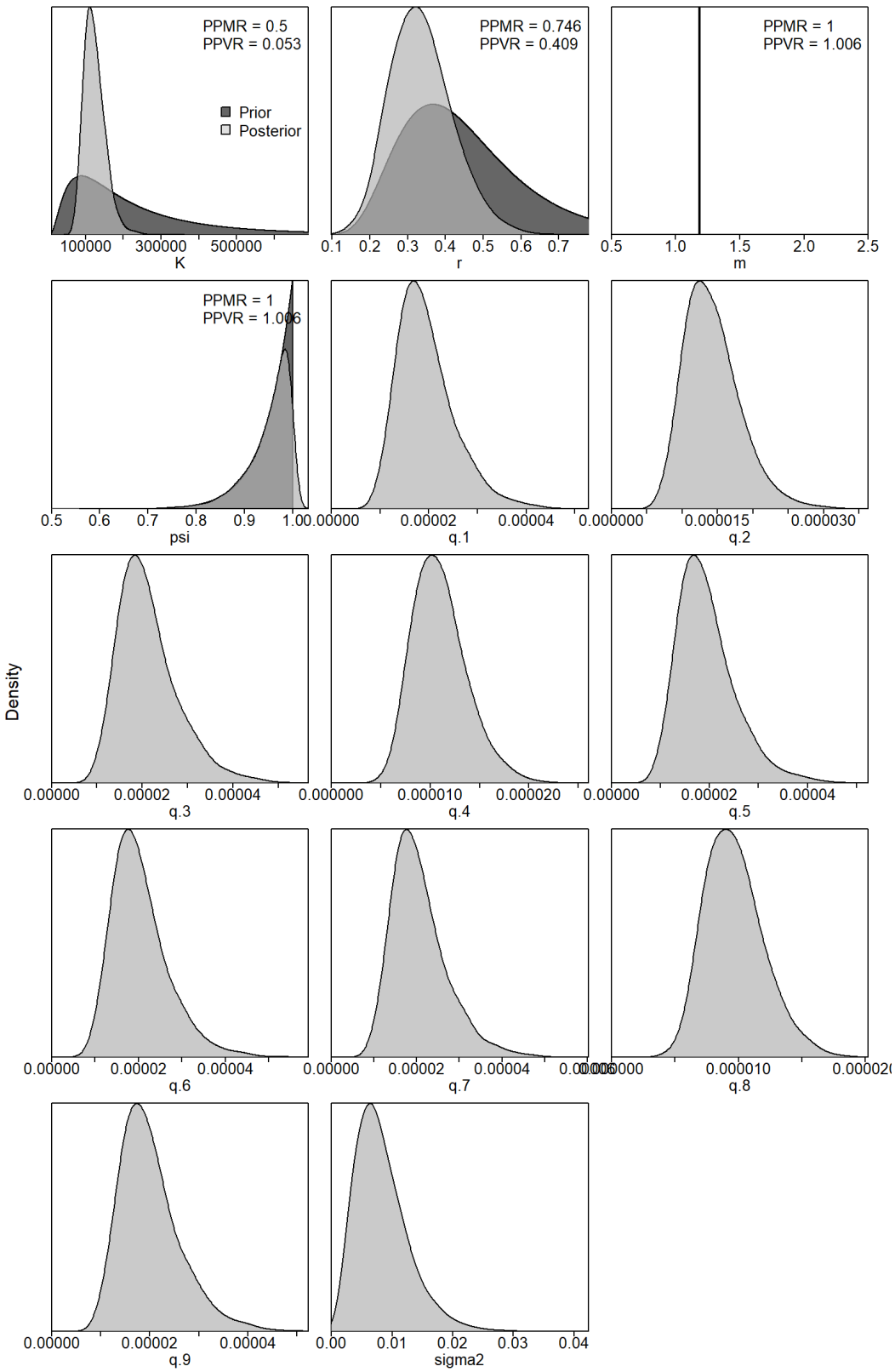


**Figure 6.** Prior and posterior distributions of various model and management parameters for the JABBA model S1 for South Atlantic swordfish. PPRM: Posterior to Prior Ratio of Means; PPRV: Posterior to Prior Ratio of Variances.

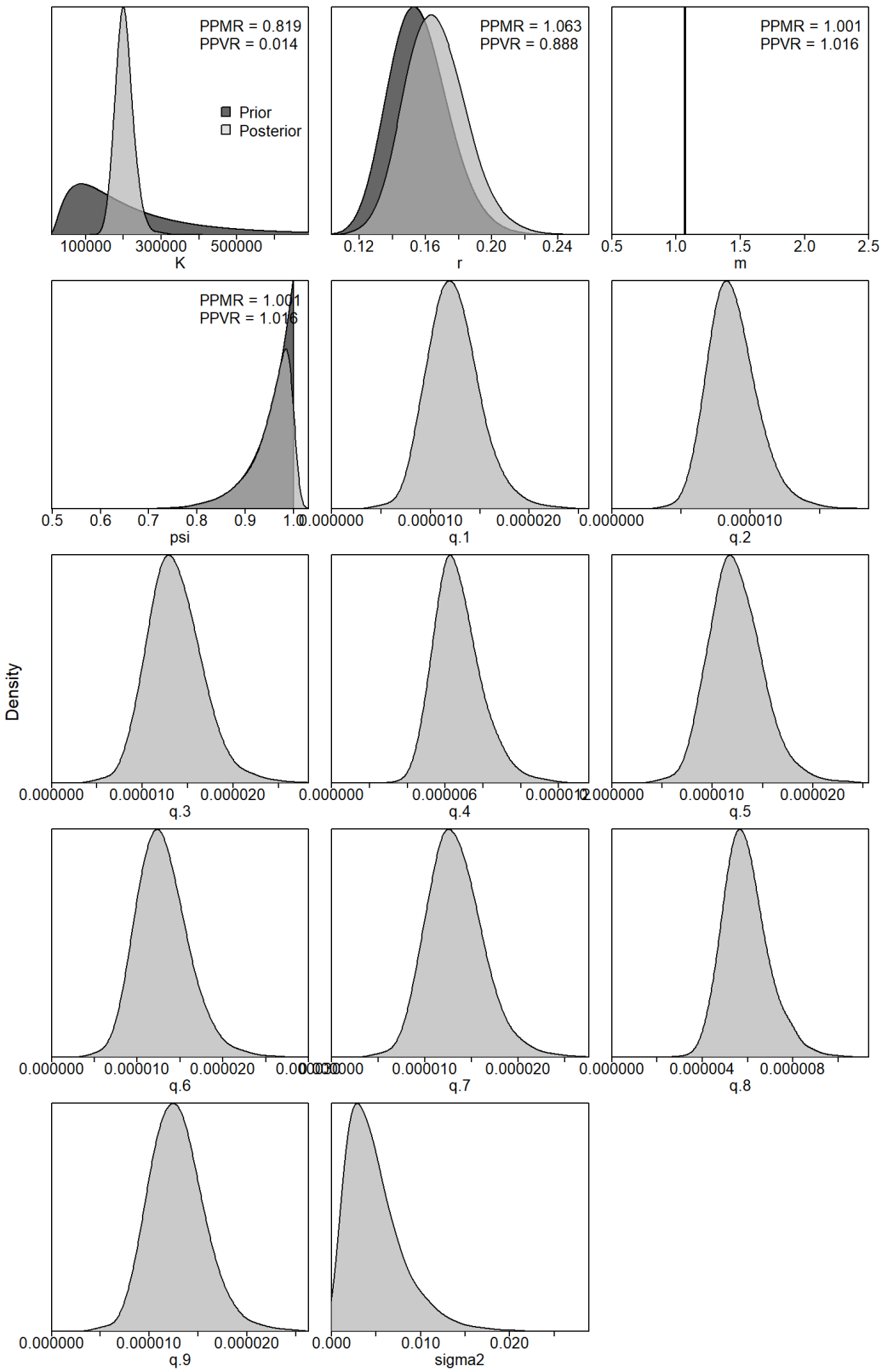


**Figure 7.** Prior and posterior distributions of various model and management parameters for the JABBA model S2 for South Atlantic swordfish. PPRM: Posterior to Prior Ratio of Means; PPRV: Posterior to Prior Ratio of Variances.

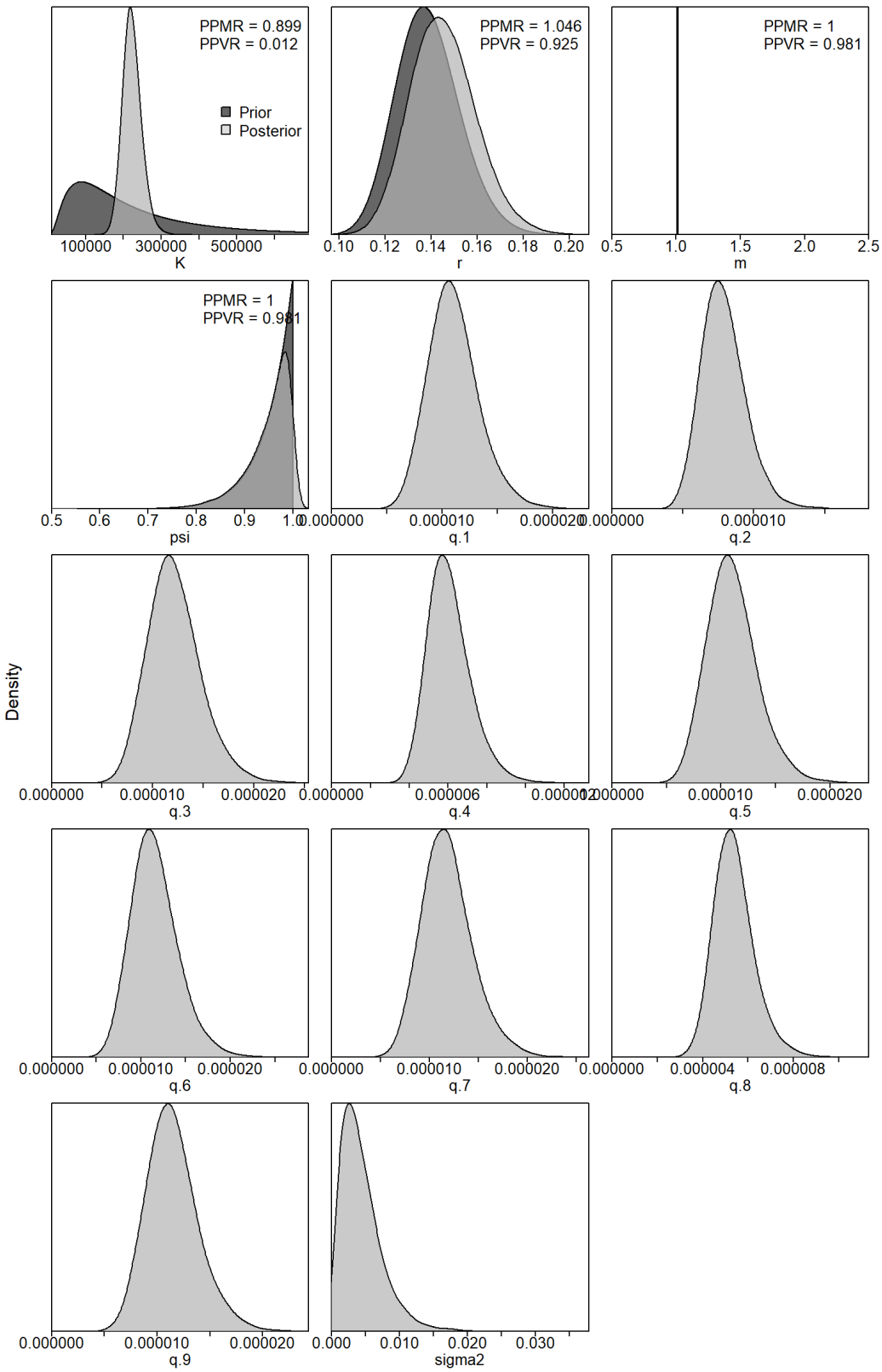


**Figure 8.** Prior and posterior distributions of various model and management parameters for the JABBA model S3 for South Atlantic swordfish. PPRM: Posterior to Prior Ratio of Means; PPRV: Posterior to Prior Ratio of Variances.

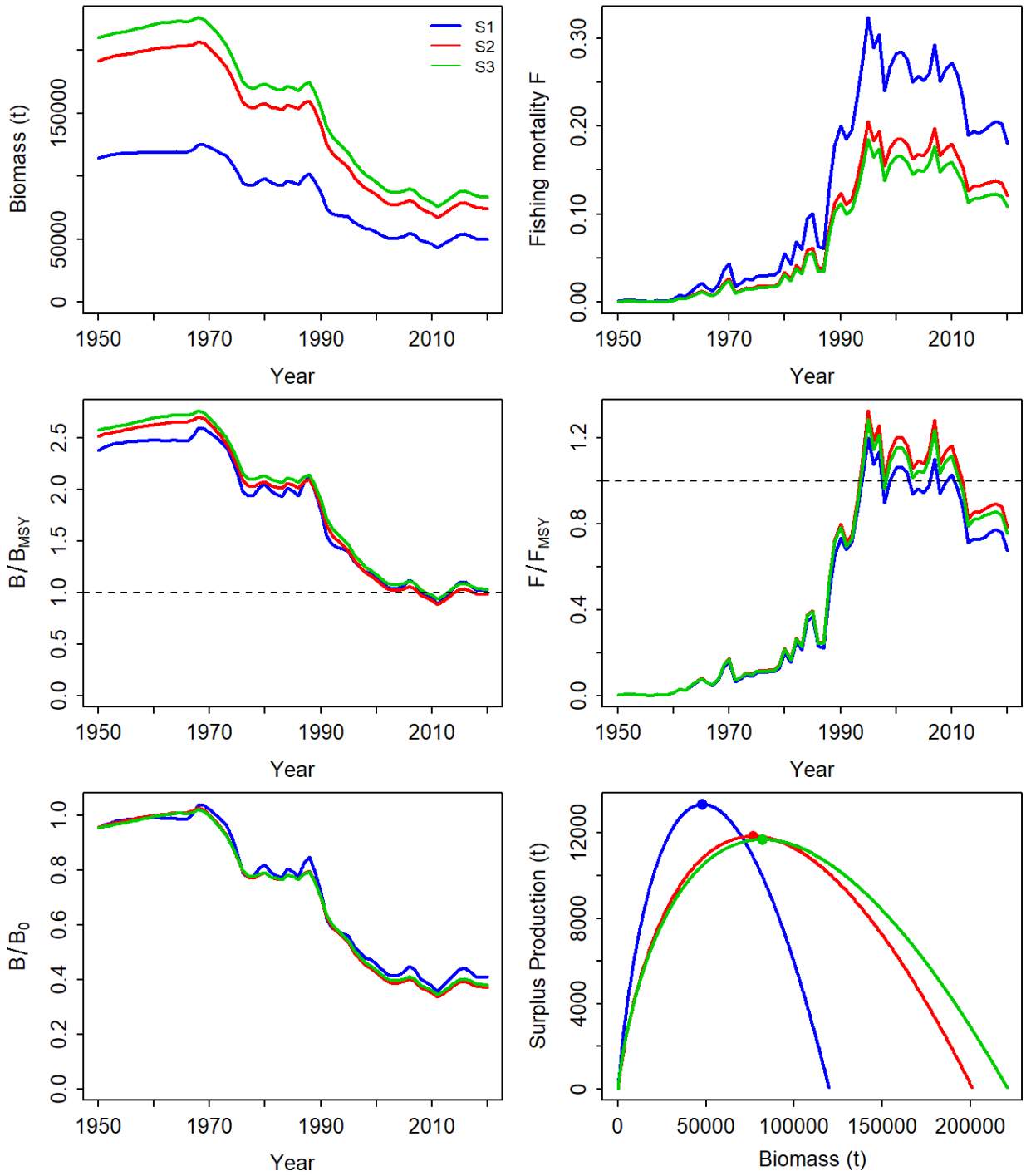


**Figure 9.** Comparison of biomass, fishing mortality (upper panels), biomass relative to *K* (*B/K*) and surplus production curve (middle panels), and biomass relative to $B_{MSY}$ ($B/B_{MSY}$) and fishing mortality relative to $F_{MSY}$ ($F/F_{MSY}$) (bottom panels) among JABBA scenarios S1- S3 for South Atlantic swordfish.

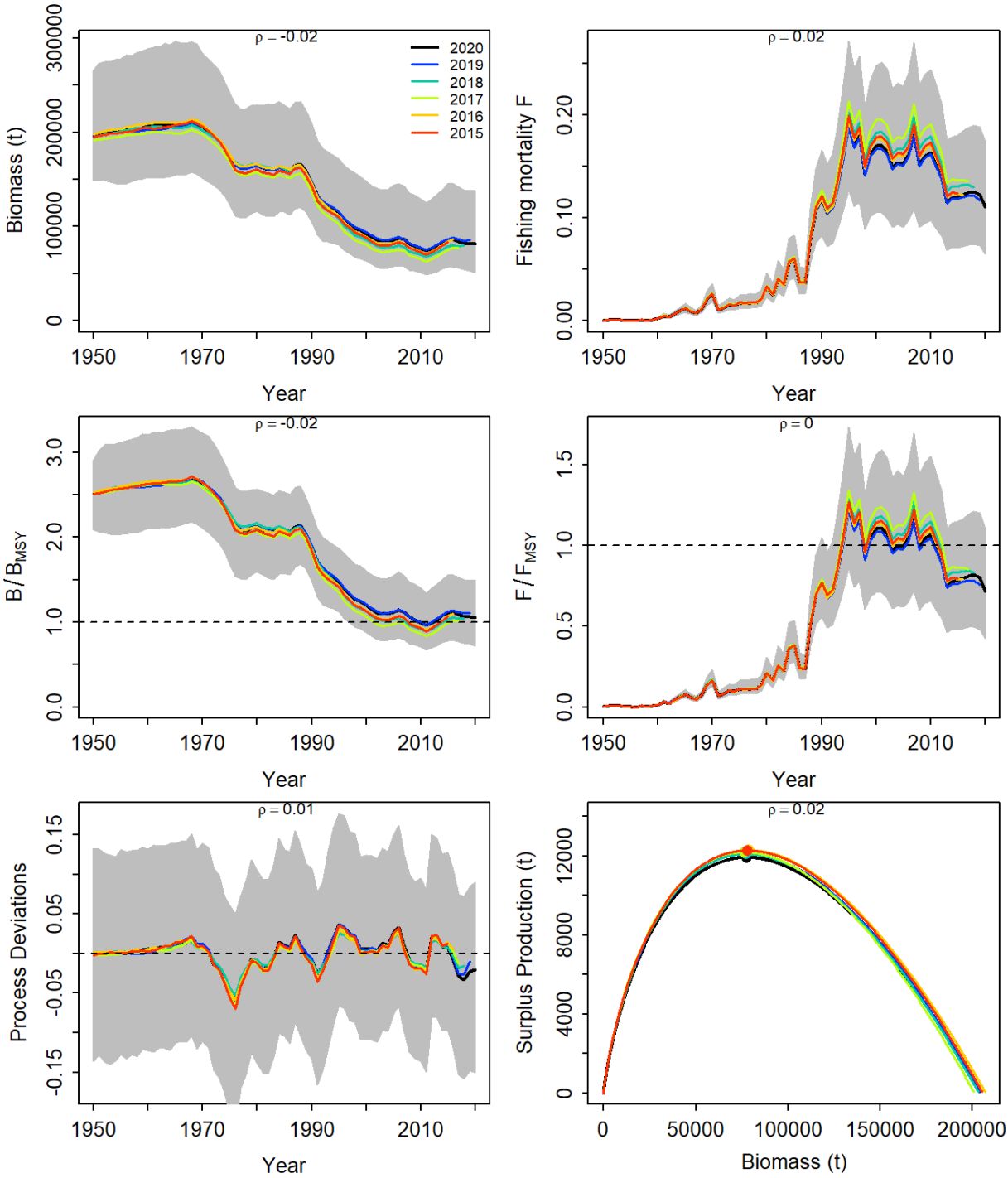


**Figure 10.** Retrospective analysis performed to the S2 JABBA model of the South Atlantic swordfish assessment, by removing one year at a time sequentially (n=5) and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to $B_{MSY}$ ($B/B_{MSY}$) and fishing mortality relative to $F_{MSY}$ ($F/F_{MSY}$) (middle panels) and biomass relative to $K$ ($B/K$) and surplus production curve (bottom panels).

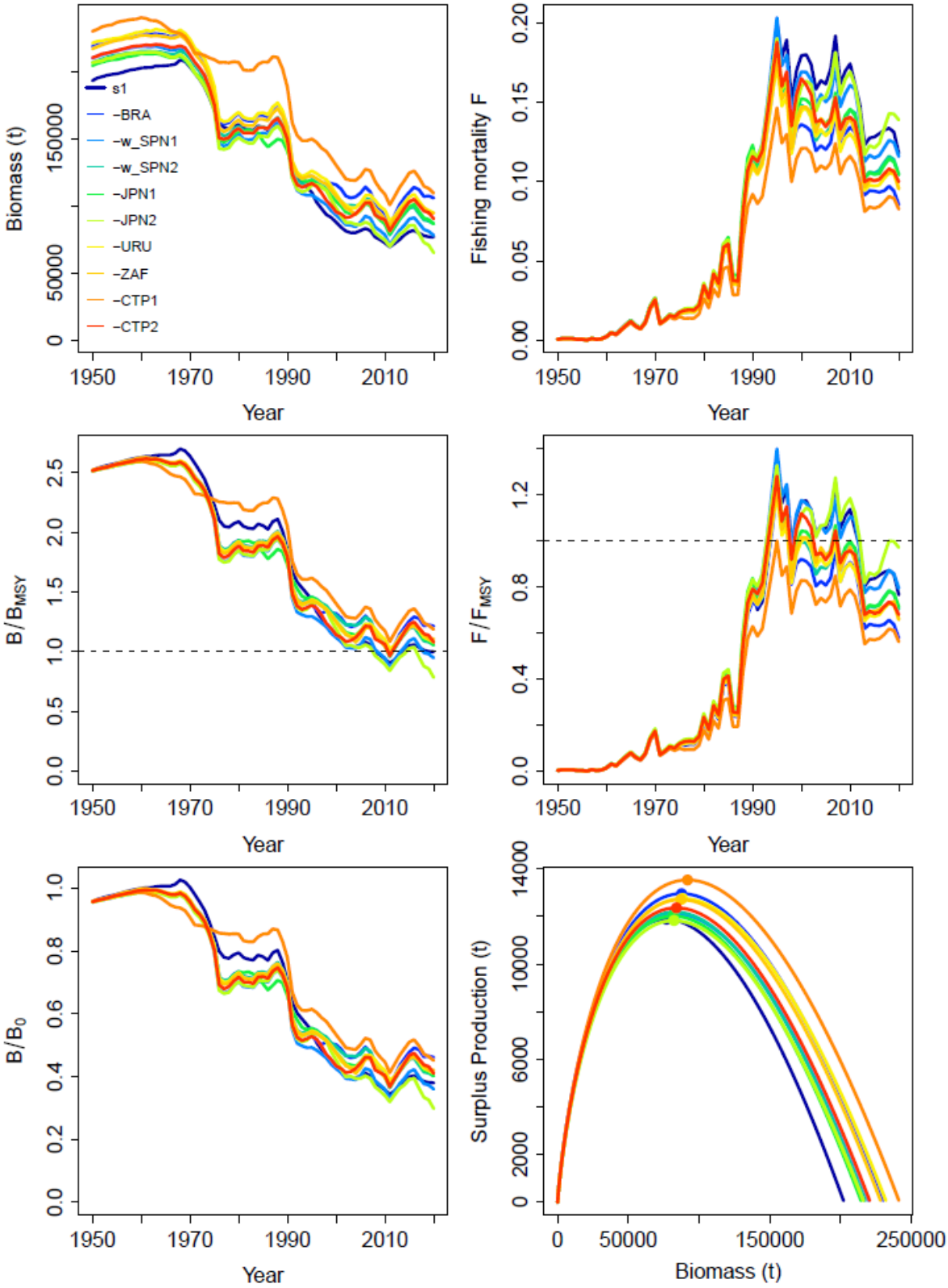


**Figure 11.** Jackknife index analysis performed to the S2 JABBA model of the South Atlantic swordfish assessment, by removing one CPUE fleet at a time and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to $B_{MSY}$ ($B/B_{MSY}$) and fishing mortality relative to $F_{MSY}$ ($F/F_{MSY}$) (middle panels) and biomass relative to $K$ ($B/K$) and surplus production curve (bottom panels)

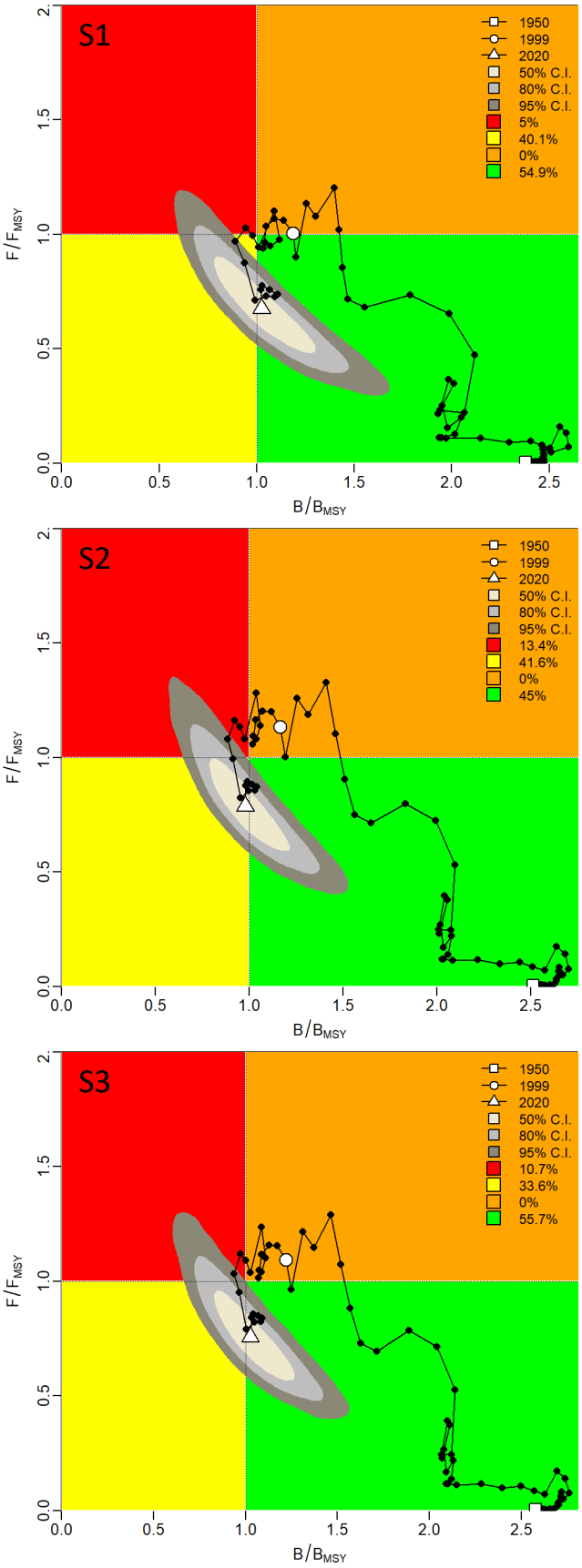


**Figure 12.** Kobe phase plot showing estimated trajectories (1950-2020) of $B/B_{MSY}$ and $F/F_{MSY}$ for the three JABBA models (S1-S3) for the South Atlantic swordfish assessment. Different grey shaded areas denote the 50%, 80%, and 95% credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

**Appendix 1**

Input parameters and results for the final JABBA Reference case model that was decided on by the Group in the SWO meeting are provided here.

***Input Parameters***

- the input r prior was objectively derived by García et al. (2016): a lognormal *r* prior of log(r) ~ N(log(0.138),0.1)
- a fixed input value of $B_{MSY}/K$ = 0.37, with steepness h = 0.7.

CPUEs

- Brazil longlines (1994-2020)
- EU-Spain longlines (1989-1999; 2000-2019)
- Japan longlines (1976-1993; 1994-2005; 2006-2019)
- Uruguay longlines (2001-2012)
- Chinese Taipei longlines (1968-1990; 1998-2020)
- South Africa longlines (2004-2020)

**Table A1.** Summary of prior values, and associated distributions, used in the JABBA reference case model for the South Atlantic swordfish.

| Parameter | Description | Prior | *m* | CV |
|---|---|---|---|---|
| *K* | Unfished biomass | lognormal | 175,000 | 100% |
| $\psi$ (*psi*) | Initial depletion | beta | 0.95 | 5% |
| $s^2$ *(proc)** | Process error variance | inverse-gamma | 0.001 | 0.001 |
| *r* | Population growth rate | lognormal | 0.155 | 12% |
| *h* | steepness | fixed | 0.7 | - |
| $B_{MSY}/K$ | Ratio of BMSY to K | fixed | 0.38 | - |
| *q* | CPUE catchability coefficient | uniform | - | - |
| *Observation error* | Std. Dev for CPUE | fixed | 0.25 | - |

* both scaling parameters set at 0.001 as Obs. Error is fixed at 0.25.

***Results***

**Table A2.** Summary of posterior quantiles presented in the form of marginal posterior medians and associated the 95% credibility intervals (5% LCI and 95% UCI) of parameters for the reference case JABBA model for South Atlantic swordfish.

| | **Median** | **LCI** | **UCI** |
|---|---|---|---|
| **K** | 196401.3 | 158348.5 | 244567.7 |
| **r** | 0.163942 | 0.132067 | 0.202944 |
| **Initial depletion** | 0.96357 | 0.825653 | 0.998642 |
| $\sigma_{proc}$ | 0.066 | 0.027 | 0.116 |
| **m** | 1.068 | 1.068 | 1.068 |
| $F_{MSY}$ | 0.154 | 0.124 | 0.19 |
| $B_{MSY}$ | 74641.26 | 60179.47 | 92946.64 |
| ***MSY*** | 11480.9 | 9793.981 | 13265.93 |
| $B_{MSY}$/**K** | 0.38 | 0.38 | 0.38 |
| $B_{1950}/K$ | 0.954 | 0.782 | 1.11 |
| $B_{2020}/K$ | 0.293 | 0.203 | 0.423 |
| $B_{2020}/B_{MSY}$ | 0.772 | 0.534 | 1.113 |
| $F_{2020}/F_{MSY}$ | 1.027 | 0.666 | 1.51 |

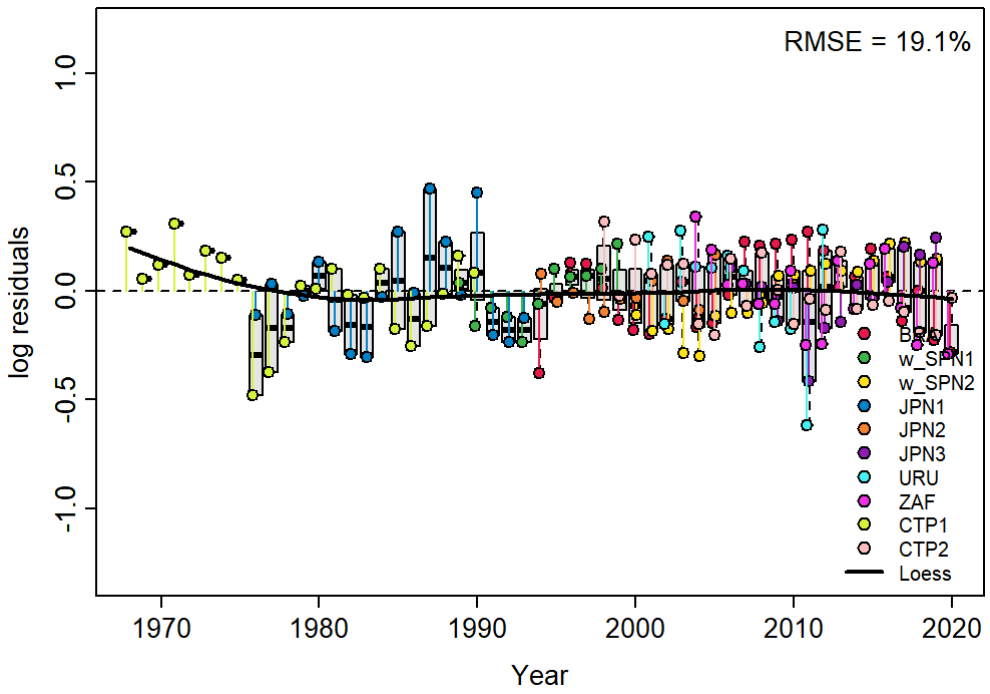


**Figure A1.** Residual diagnostic plots of CPUE indices for the South Atlantic swordfish JABBA reference case model. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a Loess smoother through all residuals.

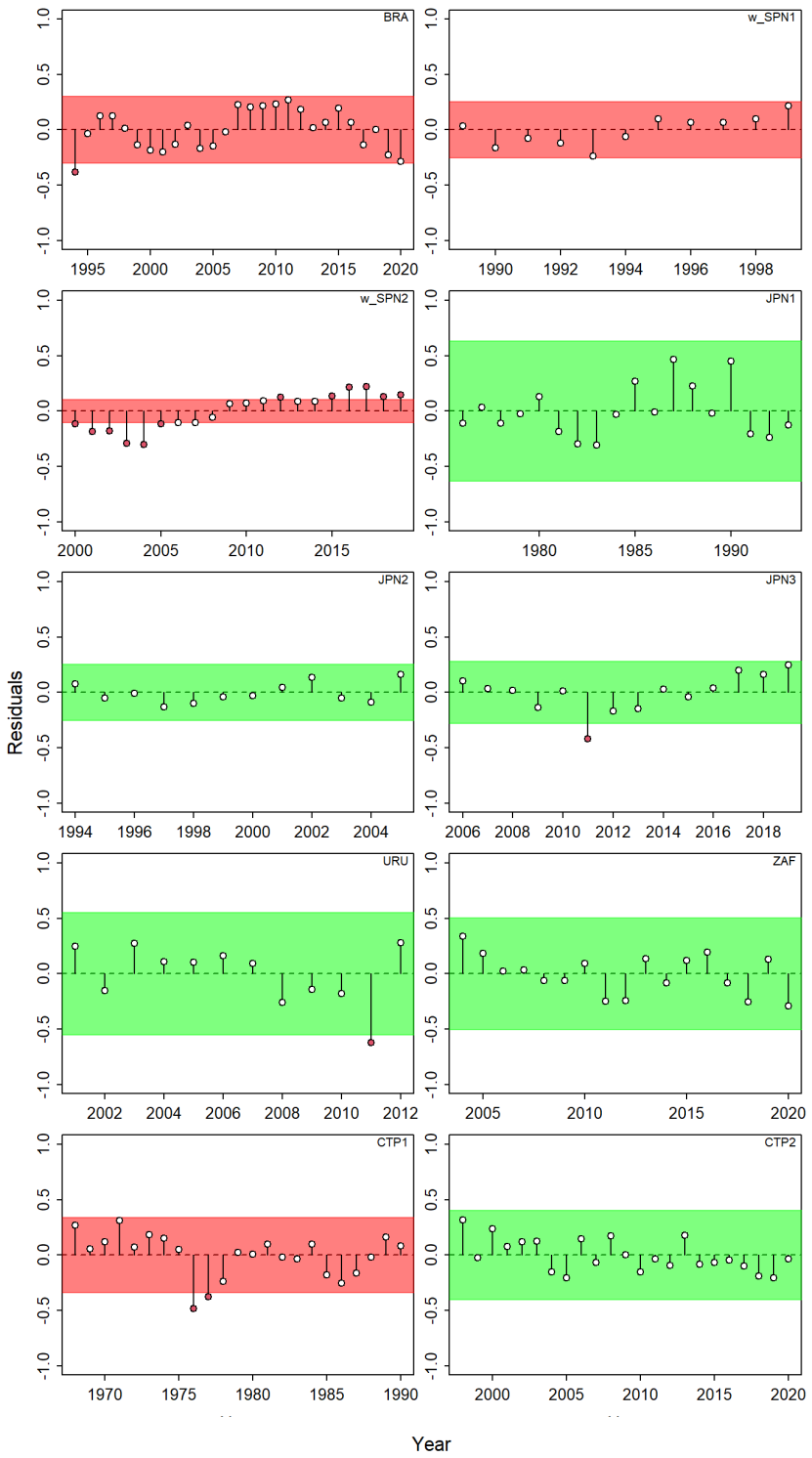


**Figure A2.** Runs tests to evaluate the randomness of the time series of CPUE residuals by fleet for the reference case model for the South Atlantic swordfish JABBA assessment. Green panels indicate no evidence of lack of randomness of time-series residuals ($p$>0.05) while red panels indicate possible autocorrelation. 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).

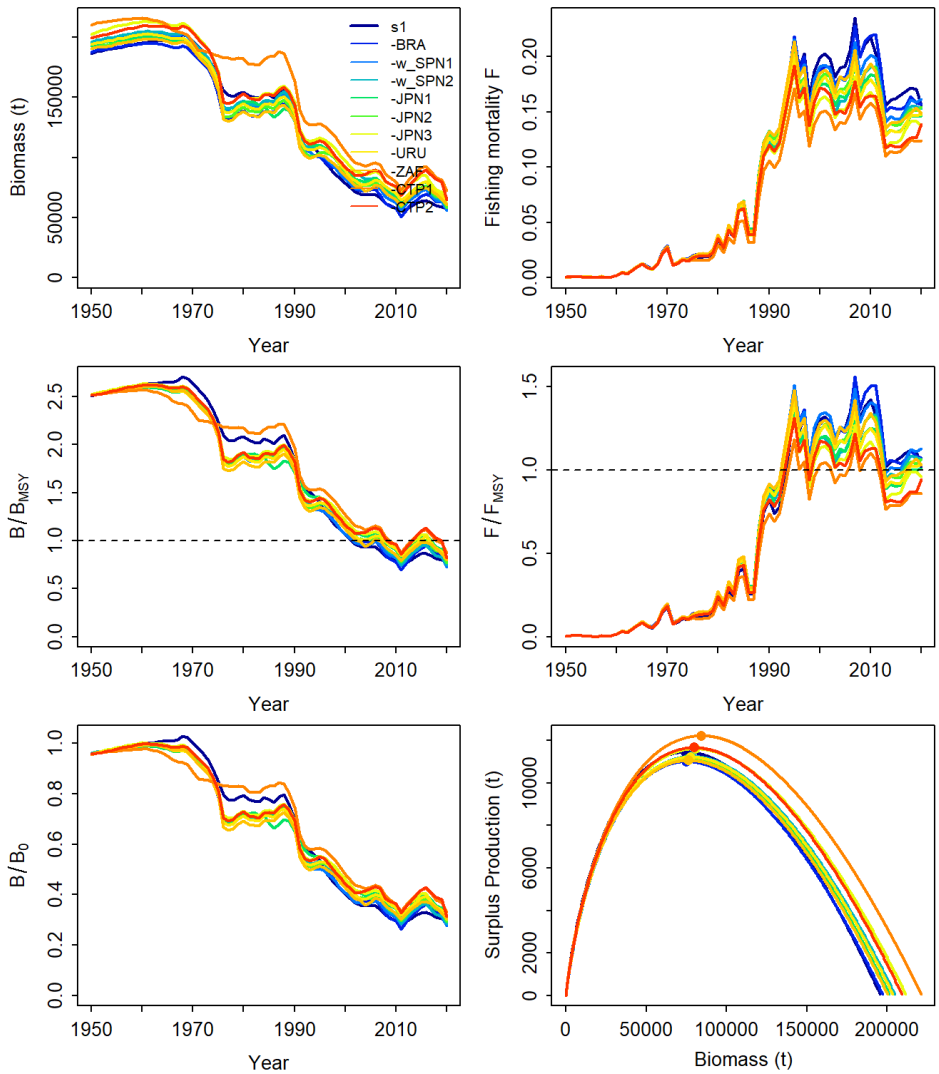


**Figure A3.** Jackknife index analysis performed to the reference case JABBA model of the South Atlantic swordfish assessment, by removing one CPUE fleet at a time and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to $B_{MSY}$ ($B/B_{MSY}$) and fishing mortality relative to $F_{MSY}$ ($F/F_{MSY}$) (middle panels) and biomass relative to $K$ ($B/K$) and surplus production curve (bottom panels).

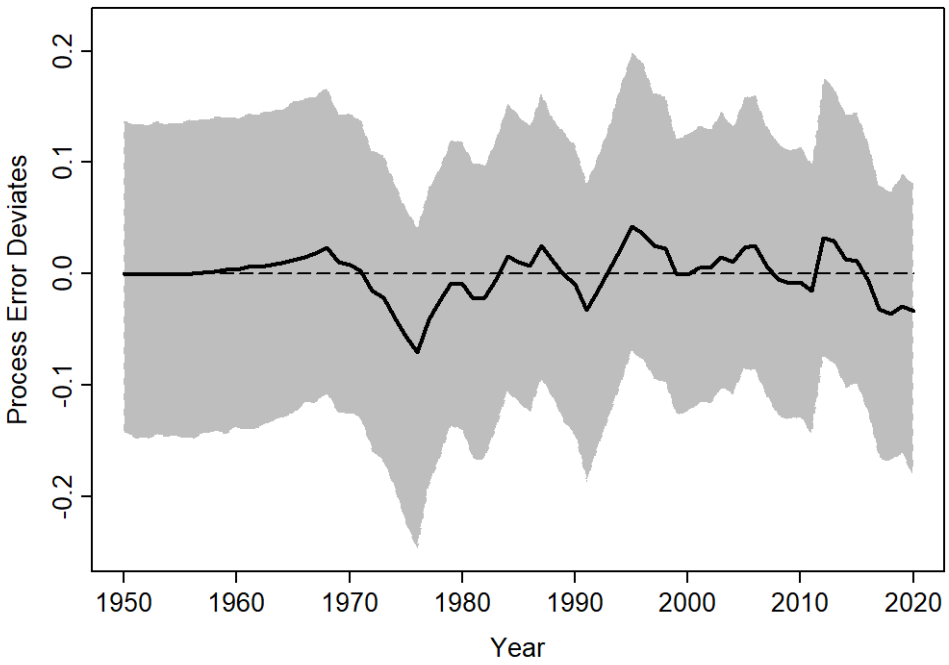


**Figure A4.** Process error deviations (median: solid line) from the reference case model for the South Atlantic swordfish JABBA assessment. Shaded grey area indicates 95% credibility intervals.

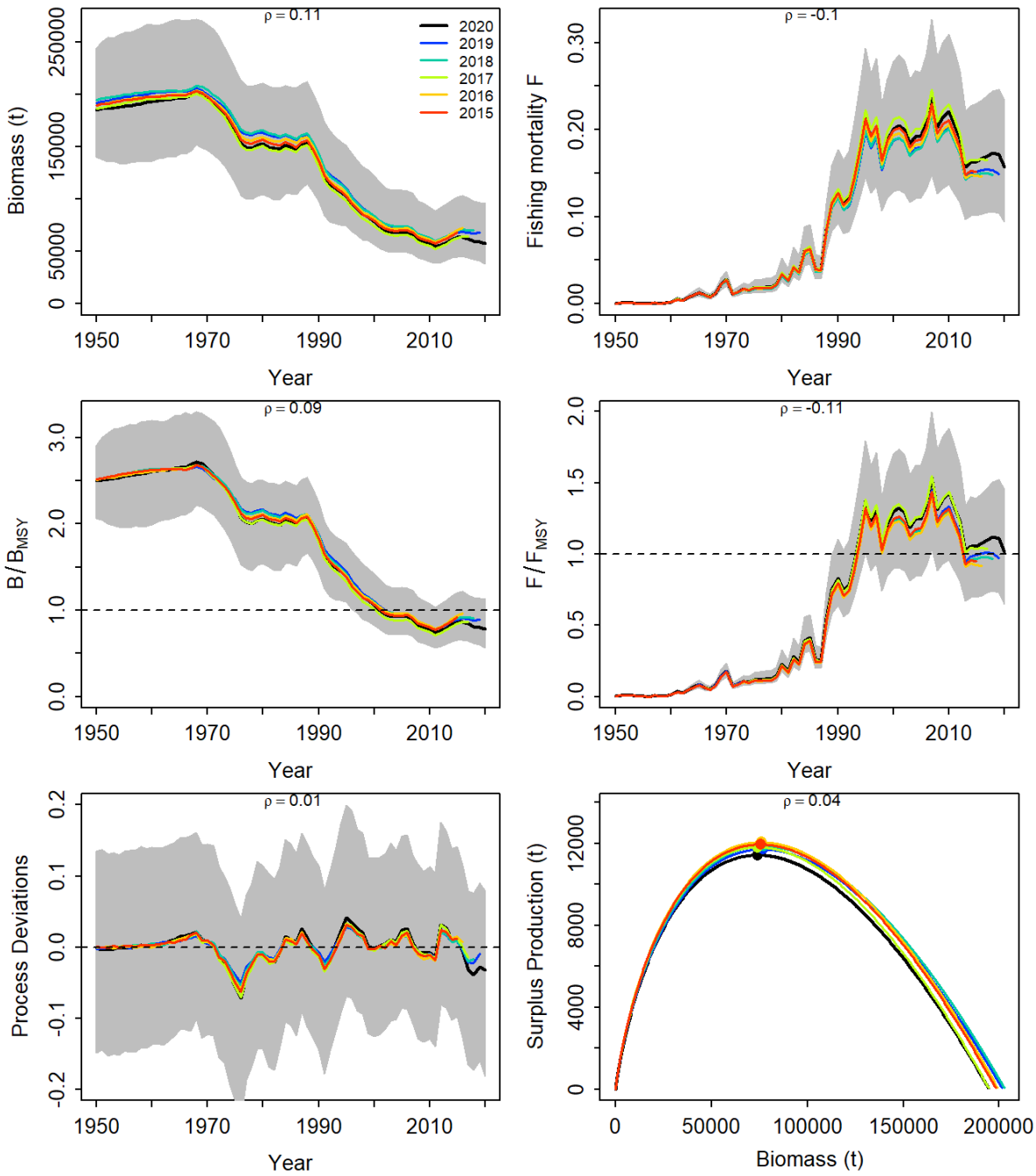


**Figure A5.** Retrospective analysis performed to the reference case model of the South Atlantic swordfish assessment, by removing one year at a time sequentially (n=5) and predicting the trends in biomass and fishing mortality (upper panels), biomass relative to $B_{MSY}$ ($B/B_{MSY}$) and fishing mortality relative to $F_{MSY}$ ($F/F_{MSY}$) (middle panels) and biomass relative to $K$ ($B/K$) and surplus production curve (bottom panels).

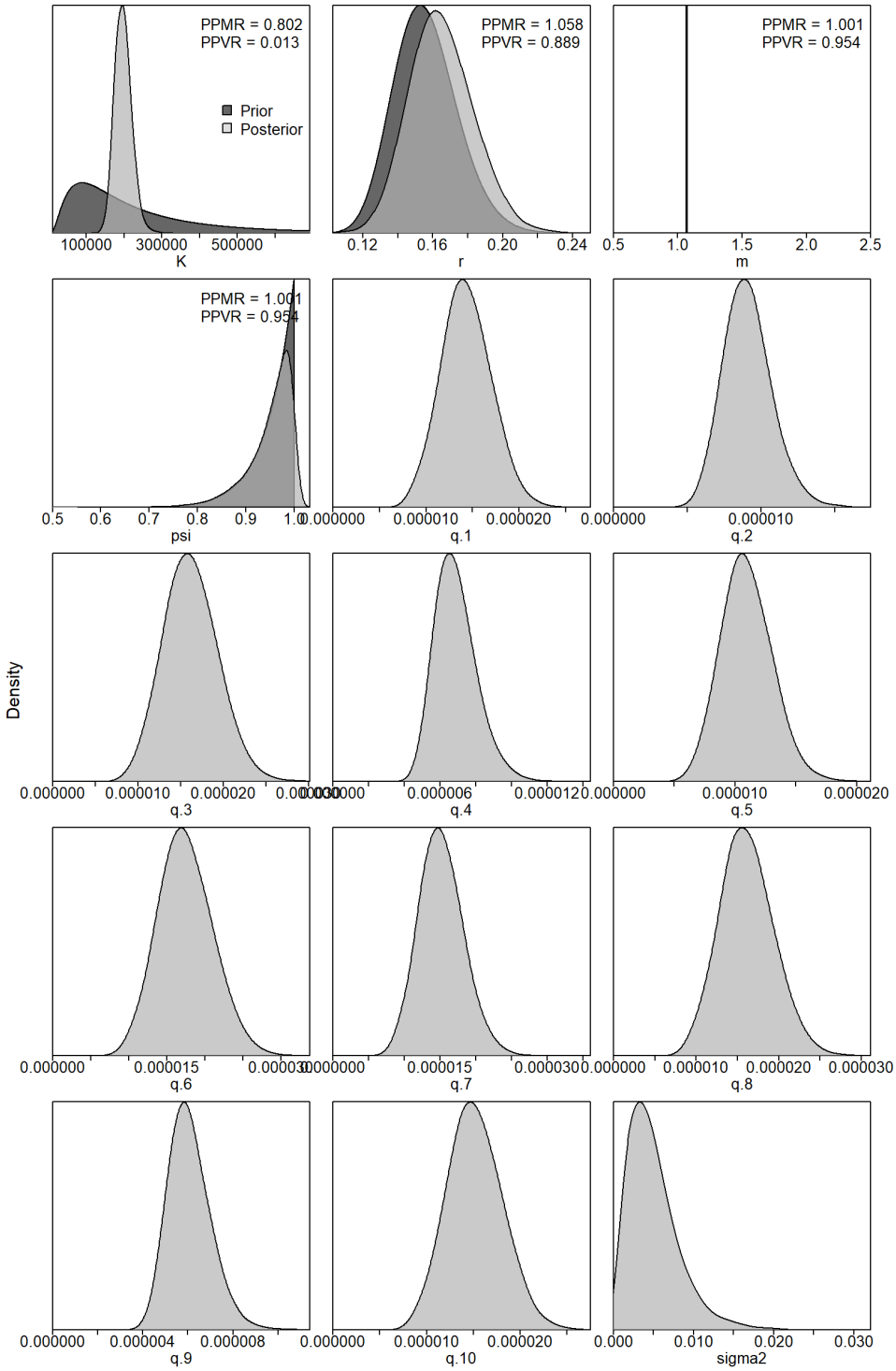


**Figure A6.** Prior and posterior distributions of various model and management parameters for the reference case model for the South Atlantic swordfish JABBA assessment. PPRM: Posterior to Prior Ratio of Means; PPRV: Posterior to Prior Ratio of Variances.

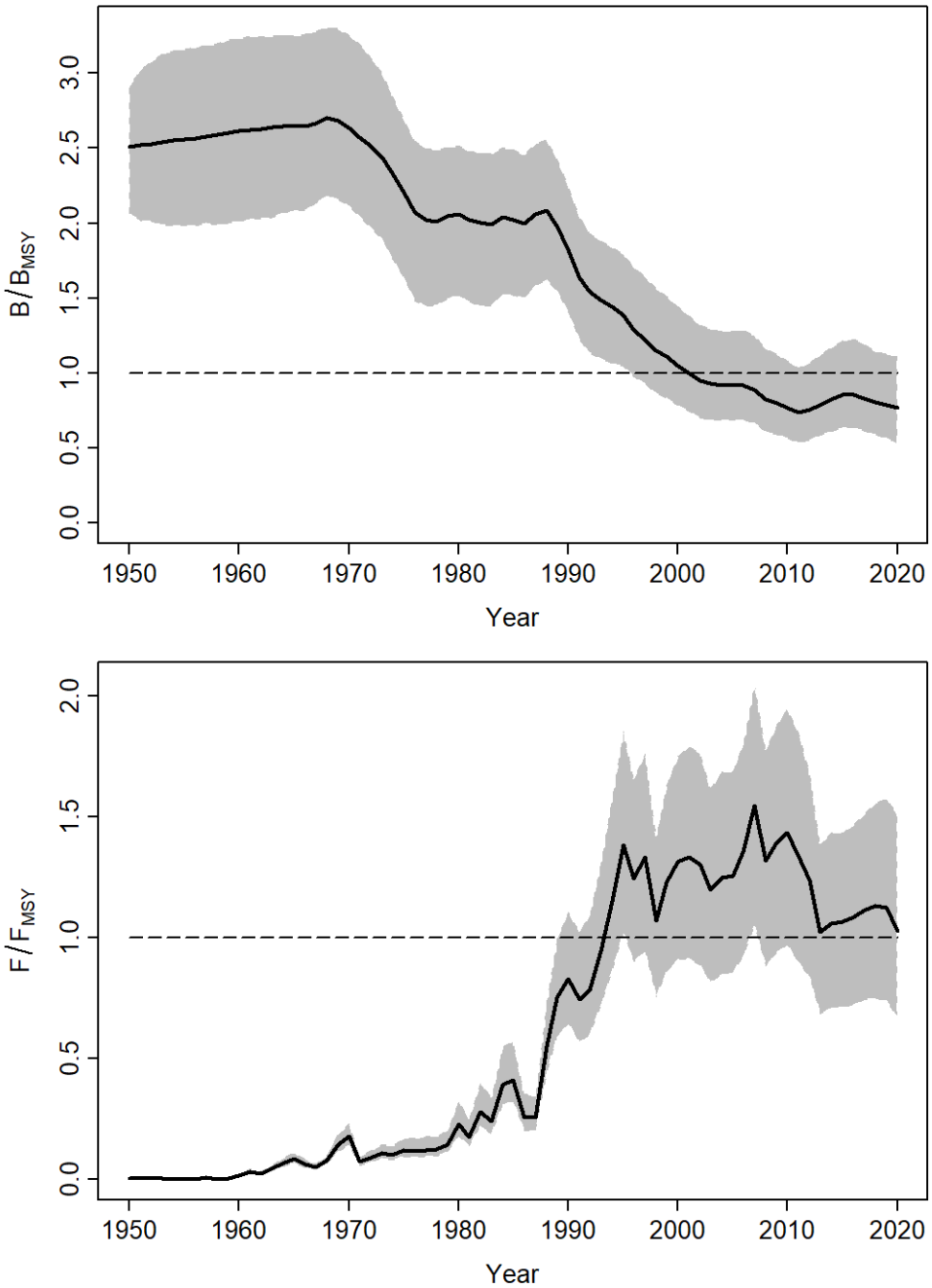


**Figure A7.** The 2022 stock assessment trends ($B/B_{MSY}$ and $F/F_{MSY}$) for the JABBA reference case model for South Atlantic swordfish.

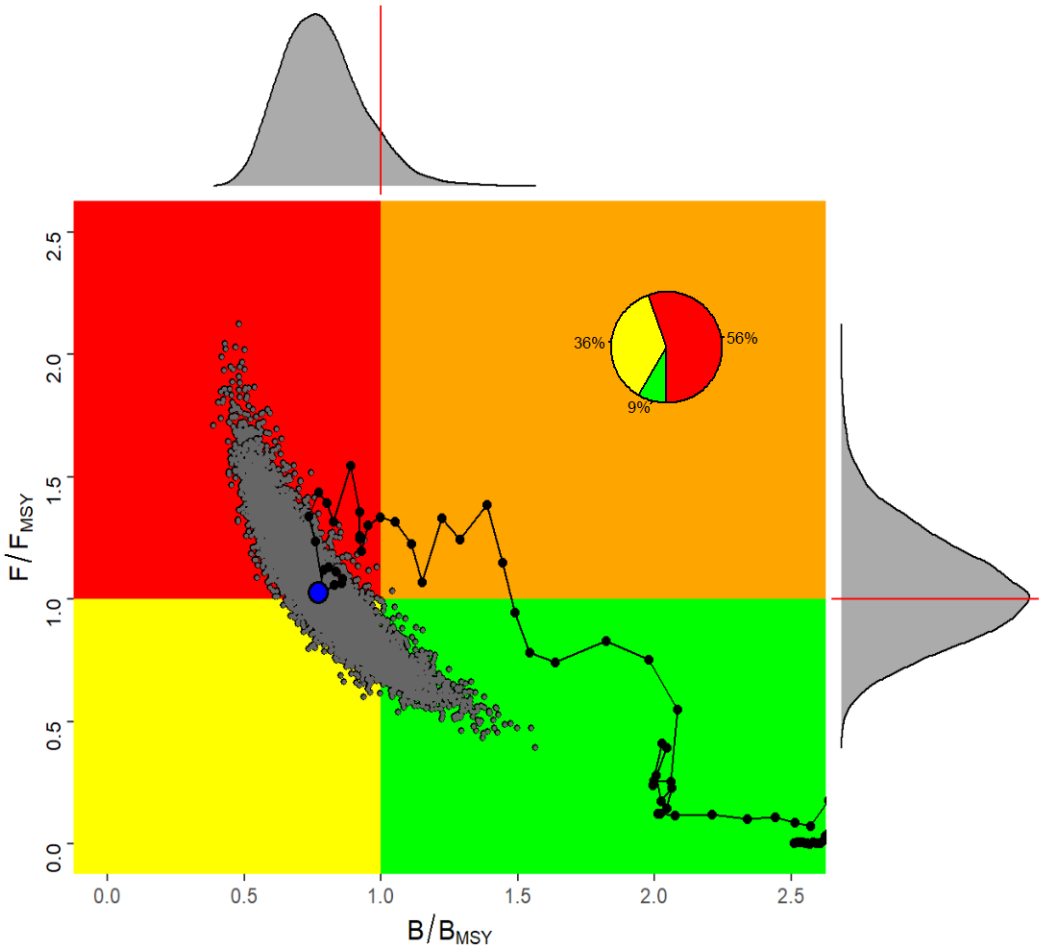


**Figure A8.** Kobe plot showing estimated trajectories (1950-2020) of $B/B_{MSY}$ and $F/F_{MSY}$ for the JABBA reference case model for the South Atlantic swordfish assessment. The probability of terminal year points falling within each quadrant is indicated in the pie chart.

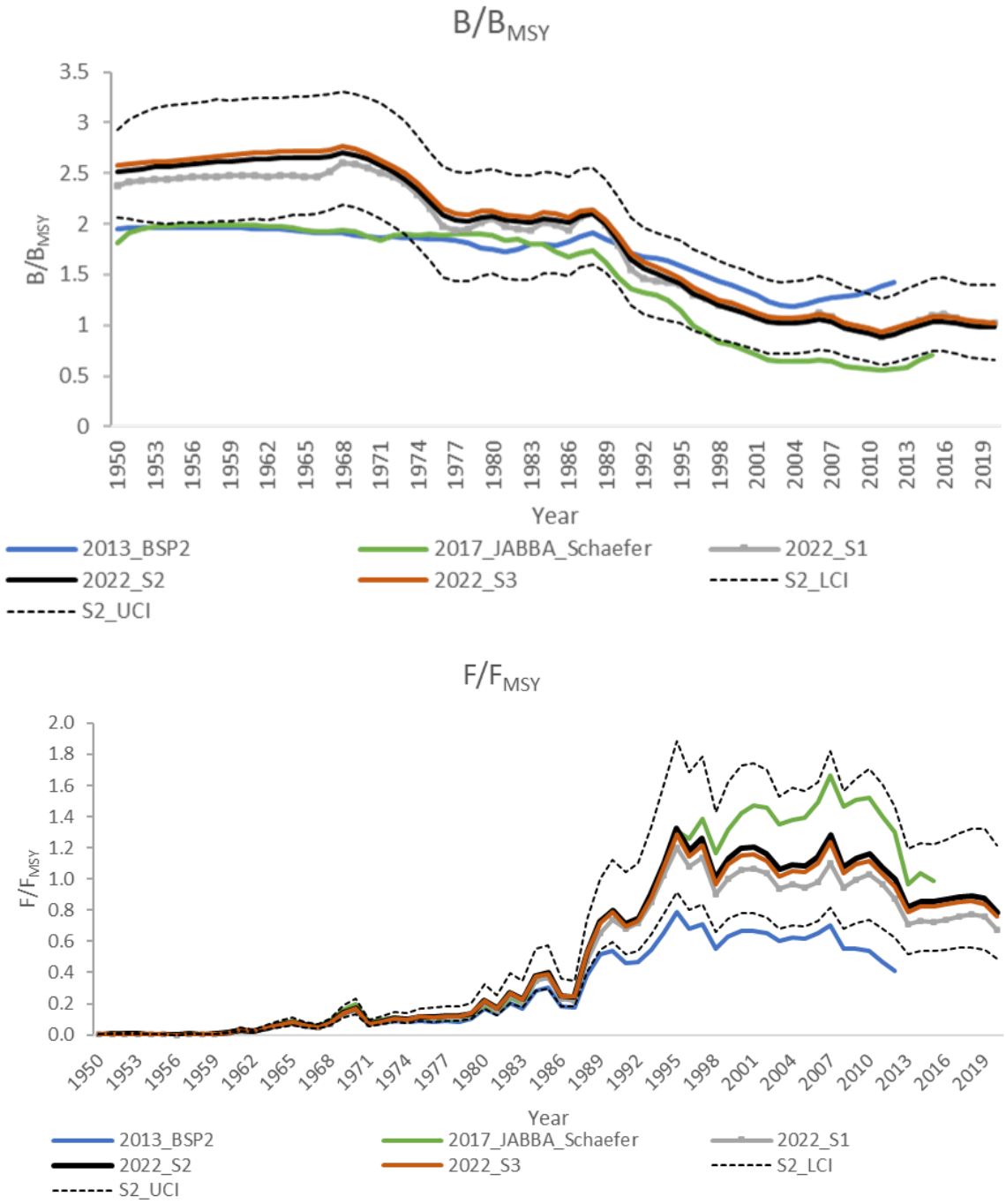


**Figure A9.** Comparisons of $B/B_{MSY}$ and $F/F_{MSY}$ estimated in the 2013, 2017, and 2022 stock assessments models (S1 – S3, not including SS models) for the South Atlantic swordfish stock.