# JABBA goes IOTC: 'Just Another Bayesian Biomass Assessment' for Indian Ocean blue shark and swordfish

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## Abstract

This working paper presents applications of the generalized Bayesian State-Space Surplus Production Model framework JABBA (Just Another Bayesian Biomass Assessment) using the recent 2017 IOTC assessments of Indian Ocean blue shark and swordfish as working examples. The assessment input data comprised multiple, partially conflicting, fisheries-depend abundance indices over varying time spans, as commonly encountered in assessments of large pelagic fishes. We therefore focus on inbuilt JABBA features for evaluating, identifying and potentially improving poor model fits, which may arise from fitting of multiple standardized CPUE time series with conflicting trends to the available catch time series. All six assessment scenarios presented here can be reproduced in less than 15 min (~ 150 seconds per run), which highlights that JABBA represents a powerful tool for rapidly producing large number of alternative scenarios, including readily presentable diagnostic and output graphs, during typically time constraint IOTC assessment workshops.

*Keywords: Bayesian, State-space framework, stock assessment, JAGS*

## 1. Introduction

The stock assessment software 'Just Another Bayesian Biomass Assessment' JABBA was applied to produce and evaluate assessment runs using the recent IOTC blue shark and swordfish stock assessments as an example. JABBA is generalized Bayesian State-Space Surplus Production Model framework that has previously been applied and tested in the 2015 ICCAT South Atlantic blue shark, the 2017 Mediterranean albacore assessment, the 2017 North and South Atlantic shortfin mako shark assessments and the 2017 ICCAT South Atlantic swordfish assessment. JABBA is coded within a user-friendly R to JAGS interface to provide a means to generate reproducible stock status estimates and diagnostics. Here, we focus on inbuilt JABBA features for evaluating, identifying and potentially improving poor fits to Indian Ocean swordfish stock assessment data that may arise from fitting of multiple

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standardized CPUE time series with conflicting trends to the available catch time series. To ensure reproducibility, JABBA will be distributed through the global open-source platform GitHub and will soon be accessible free at https://github.com/JABBA, pending formal publication of the full JABBA software documentation (Winker et al. in prep.).

## 2. Material and Methods

*2.1 Model formulation*

JABBA is generalized in the sense that the production function can take on various forms, including conventional Fox and Schaefer production functions, which can be fit based on a range of alternative error assumptions. The surplus production function is formulated in the form of the generalized three parameter by Pella and Tomlinson Surplus Production Model (SPM) (1969):

(1) $$SP_t = \frac{r}{m-1} B_{t-1}\left(1-\left(\frac{B_{t-1}}{K}\right)^{m-1}\right),$$

where $r$ is the intrinsic rate of population increase at time $t$, $K$ is the unfished biomass and $m$ is a shape parameter that determines at which $B/K$ ratio maximum surplus production is attained. If the shape parameter is $m$ = 2, the model reduces to the Schaefer form, with the surplus production (SP) attaining MSY at exactly $K/2$. If $0 < m < 2$, SP attains MSY at depletion levels smaller than $K/2$ and vice versa. The Pella-Tomlinson model reduces to a Fox model if $m$ approaches one ($m=1$) resulting in maximum surplus production at ~ $0.37K$, but there is no solution for the exact Fox SP with $m$ = 1. The shape parameter $m$ can be directly translated into $B_{MSY}/K$ and thus determines the biomass depletion level where MSY is achieved, such that:

(2) $$\frac{B_{MSY}}{K} = m^{\left(-\frac{1}{m-1}\right)}.$$

It follows that $B_{msy}$ is given by:

(3) $$B_{MSY} = Km^{\frac{-1}{m-1}},$$

and the corresponding harvest rate at MSY ($H_{MSY}$) is:

(4) $$F_{MSY} = \frac{r}{m-1}\left(1-\frac{1}{m}\right),$$

where the harvest rate $F$ is defined here as the ratio of:

(5) $F = \frac{C}{B}$ .

where $C$ denotes the catch.

We formulated JABBA building on the Bayesian state-space estimation framework proposed by Meyer and Millar (1999). The biomass $B_y$ in year $y$ is expressed as proportion of $K$ (i.e. $P_y = B_y / K$) to improve the efficiency of the estimation algorithm. The model is formulated to accommodate multiple CPUE series $i$. The initial biomass in the first year of the time series was scaled by introducing model parameter $\varphi$ to estimate the ratio of the biomass in the first year to $K$ (Carvalho et al., 2014). The stochastic form of the process equation is given by:

$$(6) \quad P_y = \begin{cases} \varphi e^{\eta_y} & \text{for } y = 1 \\ \left( P_{y-1} + \frac{r}{(m-1)} P_{y-1}\left(1 - P_{y-1}{}^{m-1}\right) - \frac{\sum_f C_{f,y-1}}{K} \right) e^{\eta_y} & y = 2,3,\ldots,n \end{cases}$$

where $\eta_y$ is the process error, with $\eta_y \sim N(0, \sigma_\eta^2)$, $C_{f,y-1}$ is the catch in year $y$ by fishery $f$.

The corresponding biomass for year $y$ is:

$$(7) \quad B_y = P_y K ,$$

The observation equation is given by:

$$(8) \quad I_{i,y} = q_i B_y e^{\varepsilon_{y,i}} \qquad y = 1, 2, \ldots, n.$$

where, $q_i$ is the estimable catchability coefficient associated with the abundance index $i$ and $\varepsilon_{y,i}$ is the observation error, with $\varepsilon_{y,i} \sim N(0, \sigma^2_{\varepsilon,y,i})$, where $\sigma^2_{\varepsilon,y,i}$ is the observation variance in year $y$ for index $i$.

## *2.2 Prior formulations*

For both species, priors were kept consistent across all the scenarios. All catchability parameters were formulated as uninformative uniform priors, while the process variance and estimable observation variance priors were implemented by assuming the following inverse-gamma distributions:

(9) $$\sigma_{\eta}^{2} \sim \frac{1}{gamma(4,0.01)}$$

(10) $$\sigma_{\varepsilon,i}^{2} \sim \frac{1}{gamma(2,0.01) + 0.25^{2}}$$

The process variance prior corresponds to mean process error of $\sigma_{\eta}$ = 0.056 (CV = 0.65). The prior for the estimable observation variance component assumes an uninformative inverse-gamma distribution with both gamma scaling parameters set to 0.001. Because most of the indices provided were deemed over-precise with CV's < 0.1, a minimum fixed observation error of 0.25 was added a priori to all time series..

*2.2.1 Blue shark*

The Schaefer Model production function was assumed for blue shark. A vaguely informative lognormal prior for K = 600,000 metric tons with a CV of 200% was assumed. For *r*, the lognormal prior (mean = log[0.267], CV = 0.075) based on updated life history analysis was specified. The initial biomass depletion prior ($\varphi = B_{1950}/K$) was inputted in the form of a lognormal prior with a CV = 0.25, assuming that the Indian Ocean stock was unexploited in 1950.

*2.2.2 Swordfish*

For swordfish we assumed a Fox production function. A vaguely informative lognormal prior for K = 200,000 metric tons with a CV of 200% was assumed. For *r*, a lognormal prior (mean = log[0.42], CV = 0.4), which closely matched the priors used for the 2017 ICCAT North and South Atlantic stock assessments. As with blue shark, the initial biomass depletion prior ($\varphi = B_{1950}/K$) was inputted in the form of a lognormal prior with a CV = 0.25, assuming that the Indian Ocean stock was unexploited in 1950.

*2.3 Scenarios*

During the 2017 IOTC stock assessments of blue shark and swordfish, the evaluation of alternative scenarios specifically focused on identifying and improving poor fits to CPUE series that may arise from fitting of multiple standardized CPUE time series with conflicting trends to the available catch time series (Figs 1). For Indian Ocean blue shark, three alternative catch time series estimations were made available prior to the assessment: (1) Nominal, (2) GAM and (3) EUROPA. However, for the purpose of this report, we only present assessment runs based on the GAM catch series, which represents substantially raised catch estimates compared to the Nominal data, starting in 1950 (Fig 1a).

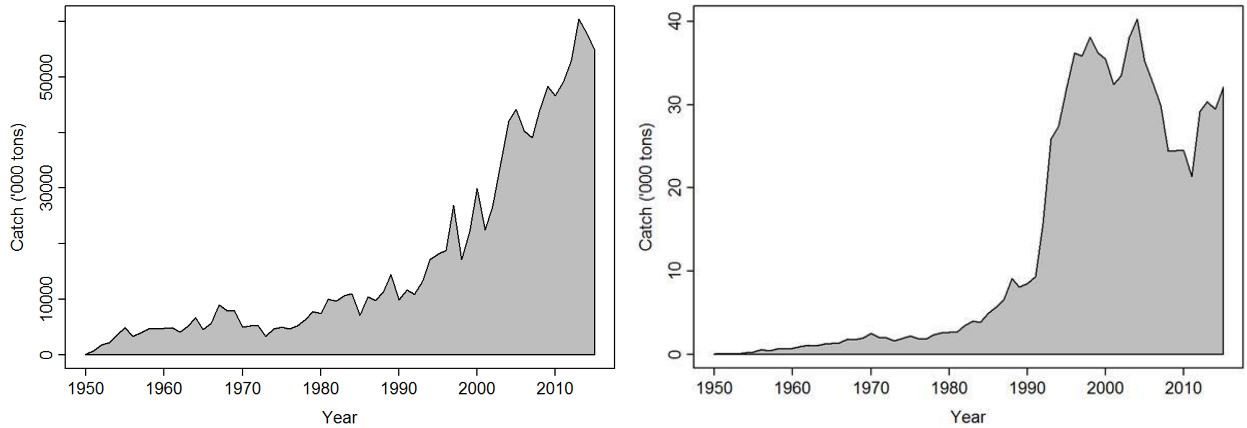


**Fig.1.** Total catch estimates for Indian Ocean blue shark (left) and swordfish (right) for the period 1950-2015.

*2.4.1 Blue shark CPUE scenarios*

A total of 7 standardized CPUE time series from longline fisheries were available for the 2017 blue shark assessment. These were (1) Japan early (JPN1, 1971-1993), (2) Japan late (JPN2, 1992-2015), (3) Portugal (EU-POR, 2000-2015), (4) Reunion (EU-FRA, 2007-2015), (5) Indonesia (IND, 2005-2015), Spain (EU-ESP, 2001-2015) and Chinese-Taipei (CH-TAI, 2004-2015). Initially, the standardized CPUE indices were separated into two groups, with Group 1 including JPN1, JPN2, EU-POR, and EU-FRA and Group 2 including JPN1, JPN2, EU-ESP, IND and CH-TAI. The third scenario included all CPUE time series. Based on initial JABBA fits and residual diagnostics, Group 1 was selected as the base-case Scenario 1, which also excluded the early JPN1 CPUE index because of concerns of adequate blue shark catch reporting and potential issues related to data filtering procedures. The alternative run, including all CPUE indices, was retained for comparison leading to the following two scenarios which were evaluated assuming the Schaefer form of the production function:

**Scenario 1:** JPN2, EU-POR and EU-FRA with the "GAM" catch series (base-case)

**Scenario 2:** All indices with the "GAM" catch series

Scenario 2 was used as a reference case to conduct sensitivity runs by dropping one CPUE index at a time. Sensitivity was assessed with respect to the stock status estimates $B/B_{MSY}$ and $F/F_{MSY}$.

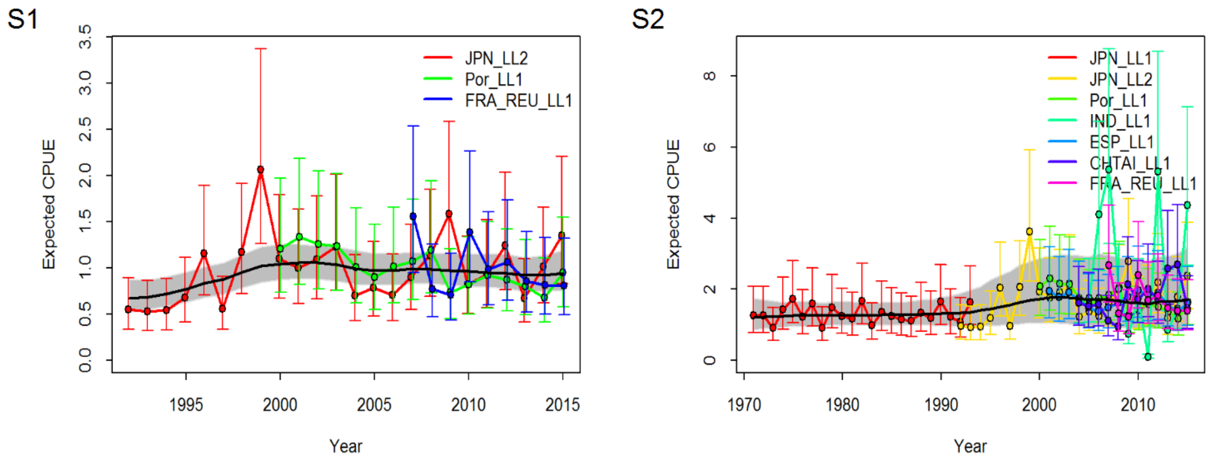


**Fig. 2**. Aligned CPUE indices according to Scenarios 1-2 (S1-S2) for Indian Ocean blue shark, which were produced using the state-space CPUE averaging tool implemented in JABBA. The underlying abundance trend is treated as an unobservable state variable that follows a log-linear Markovian process, so that the current mean relative abundance was assumed to be a function of the mean relative abundance in the previous year, an underlying mean population trend and lognormal process error term. The CPUE indices are aligned with the base index via estimable catchability scaling parameters.

### *2.5.2 Swordfish CPUE scenarios*

Following evaluations of initial assessment fits based on a variety of modelling frameworks, including fits from Stock Synthesis 3 (ss3) as well as deterministic (APSIC) and state-space Bayesian Surplus Production Models, the WPB considered the years 1994-1999 of the standardized CPUE series from Japan (JPN.II) and the EU-POR CPUE index for the period 2000-2015 as primary inputs for a potential base-case scenario. In this working paper, we specifically evaluate the effects of adding additional CPUE indices in terms of model fits, stock status and associated uncertainty. The additional CPUE indices were selected among the least likely to cause data conflicts with the two primary CPUE indices JPN.II and EU-POR. The additional CPUE indices identified were: (1) the extended Japanese CPUE series (1994-2015; JPN.II), (2) the South African CPUE series (2004-2015; ZAF) and (3) the second part of the Taiwanese CPUE series (1994-2015; TAI.II). According to the sequential addition of each CPUE index (Fig. 3), the following four scenarios were formulated:

**Scenario 1:** JPN.II3 (1994-1999) + EU-POR (2000-2015)

**Scenario 2:** JPN.II (1994-2015) + EU-POR (2000-2015)

**Scenario 3:** JPN.II (1994-2015) + EU-POR (2000-2015) + ZAF (2004-2015)

**Scenario 4:** JPN.II (1994-2015) + EU-POR (2000-2015) + ZAF (2004-2015) + TAI.II (1994-2015)

In addition, Scenario 4 was used as a reference case to conduct sensitivity runs by dropping one CPUE index at a time. Sensitivity was assessed with respect to the stock status estimates $B/B_{MSY}$ and $F/F_{MSY}$.

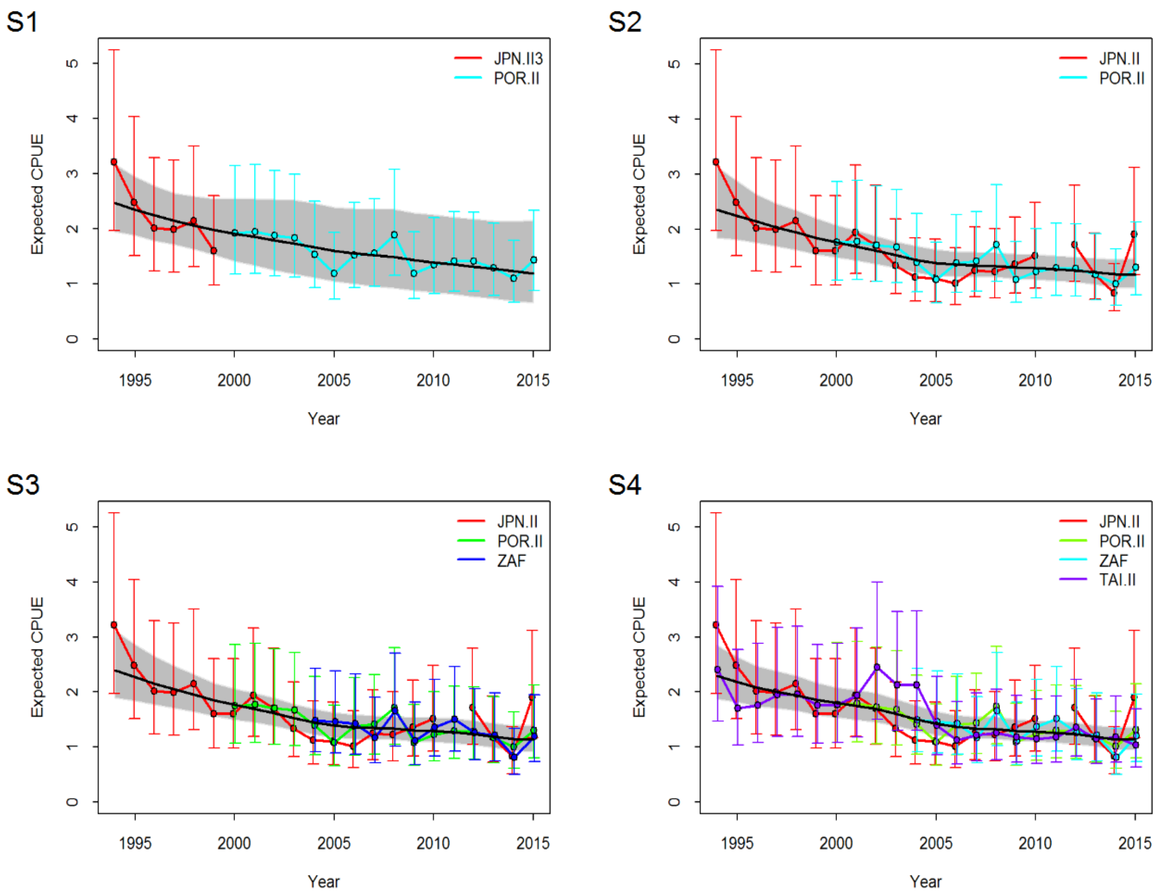


**Fig. 3**. Aligned CPUE indices according to Scenarios 1-4 (S1-S4) for Indian Ocean swordfish, which were produced using the state-space CPUE averaging tool implemented in JABBA. The underlying abundance trend is treated as an unobservable state variable that follows a log-linear Markovian process, so that the current mean relative abundance was assumed to be a function of the mean relative abundance in the previous year, an underlying mean population trend and lognormal process error term. The CPUE indices are aligned with the base index via estimable catchability scaling parameters.

## 3. Results and Discussion

### *3.1. Convergence*

All but the swordfish Scenario 4 JABBA model runs showed robust convergence diagnostics. Although the Heidelberger and Welch test could not reject the hypothesis that the MCMC chains were stationary at the 95% confidence level for any of the estimable parameters for all scenarios, the swordfish Scenario 4 showed some severe distortion in the process error deviance (Fig. 4), which also resulted in implausible result outputs. Further evidence of model misspecification was that the process error estimate exceeded 0.2 (Thorson et al., 2014). By subsequently increasing the fixed variance component from $0.25^2$ to $0.3^2$ and thereby down-weighing the CPUE indices, it was possible to achieve a more stationary process error deviance that also resulted in interpretable assessment outputs for the swordfish Scenario 4.

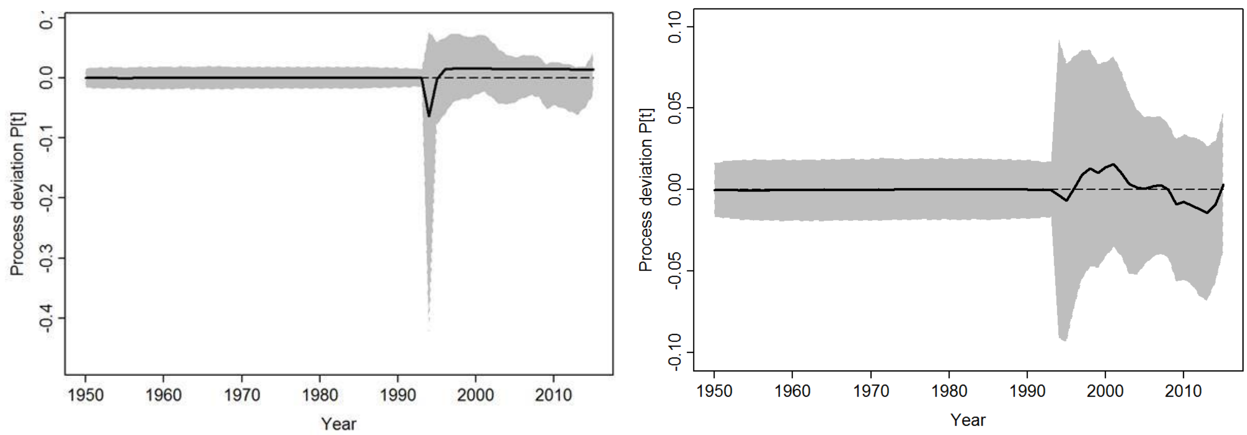


**Fig. 4.** Process error deviations trajectories for the swordfish Scenario 4, run with two different fixed observation variance components of $0.25^2$ (left) and $0.3^2$ (right)

### *3.2.1 Blue shark CPUE fits and sensitivity*

A summary of the model fit statistics for the blue shark Scenarios 1 and 2 is presented in Table 1. Adding all available CPUE indices to the JABBA model had a notably negative effect on the goodness of the fit as judged by the RMSE, but also helped to substantially increase the residual degrees of freedom (DF) as an indicator of predictive power.

**Table 1**: Summary of JABBA fit statistics for Indian Ocean blue shark. $N_{obs}$: Number CPUE observations, $N_p$: Number of model parameters, DF: Residual degree of freedom, Root-mean-squared-error (RSME), Deviance Information Criterion (DIC).

| Statistic | Scenario 1 | Scenario 2 |
|---|---|---|
| $N_{obs}$ | 49 | 110 |
| $N_p$ | 10 | 18 |
| DF | 39 | 92 |
| RMSE(%) | 32.3 | 46.5 |
| DIC | -95 | 80.3 |

For Scenario 1, the first few CPUE values of the JPN index showed a systematic departure in the residual pattern, whereas after 2000, CPUE residuals fluctuated more evenly around 0 (Fig. 5). The underlying residuals trends CPUE appeared to be consistent between the EU-POR and EU-FRA indices, which both indicated conflicts in trends with the JPN index (Fig. 3). By contrast, Scenario 2, which included all CPUE series, revealed a lack of fit for several indices in recent years (Fig. 5). In particular, the IND index resulted in a poor fit, while ESP-EU and CH-TAI showed notably correlated residual patterns. The addition of a number of poorly fitting indices can largely explain improved fit of Scenario 1 compared to Scenario 2 in terms of the RMSE (Fig. 5), with the latter decreasing from 46.5% for Scenario 2 to 32.3% for Scenario 1. Comparisons of observed and predicted CPUE indices for individual time series are shown in Appendix I (Figs. A1-A2).

The sensitivity analysis of the complete set of CPUE indices demonstrated, however, that the stock status estimates for *B / $B_{MSY}$* and *F / $F_{MSY}$* were generally fairly insensitive to excluding any one CPUE series at a time (Fig. 6). The most sensitive CPUE indices were JPN1 and JPN2. While excluding the JPN1 index only affected the *B/$B_{MSY}$* trajectory retrospectively, the exclusion of the JPN2 index showed stronger effects on current stock status estimates, which were more pessimistic both in terms of *B/$B_{MSY}$* and *F/$F_{MSY}$*. Although excluding the IND index had no discernible influence on either *B/$B_{MSY}$* or *F/$F_{MSY}$*, it resulted in a substantial decrease in the residual-mean-squared-error (Fig. 6), thus indicating an overall improvement of the goodness-of-fit.

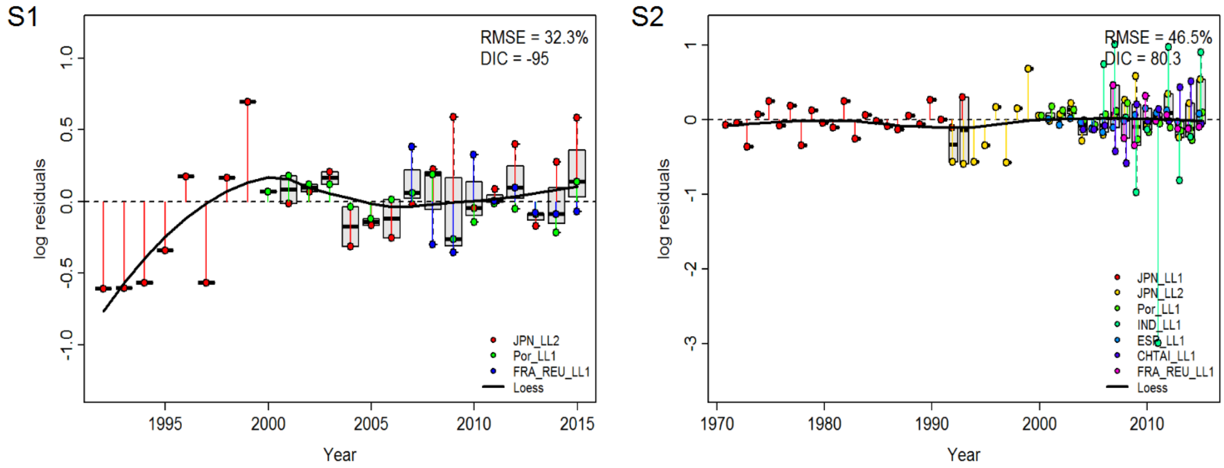


**Fig. 5.** JABBA residual diagnostic plots for the Schaefer model scenarios (S1-S4) for Indian Ocean blue shark showing the log-residuals for CPUE series. Loess smoothers were fitted across all CPUE residuals and the width of the boxplots illustrates the relative extend of conflicts among CPUE residuals. The Residual-Mean-Error (RMSE%) is provided as good-of-the-fit metric together with the DIC.

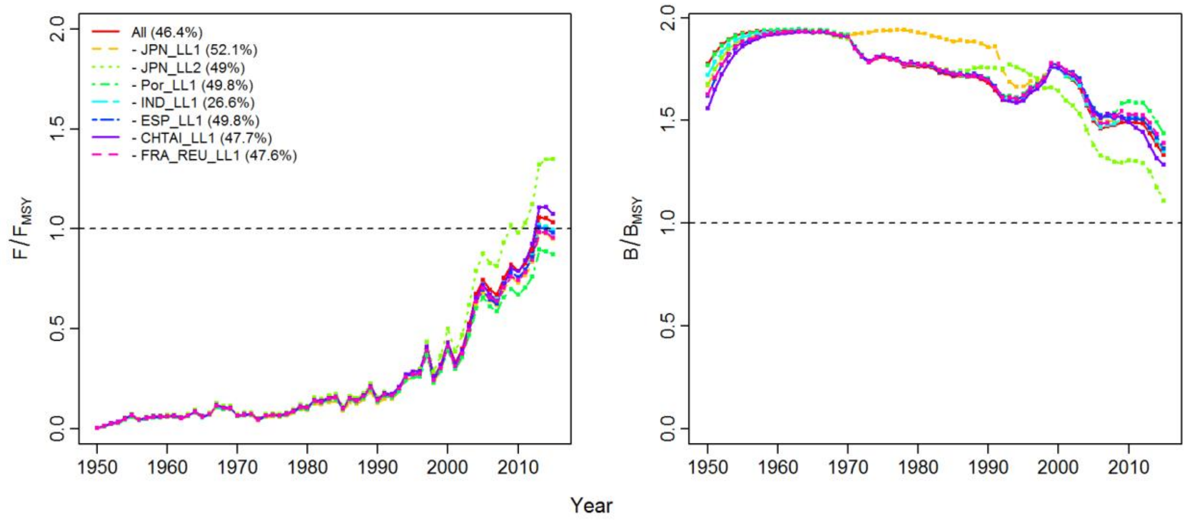


**Fig. 6.** Sensitivity analysis showing the effects of excluding one CPUE index at the time on the stock status estimates of *F* /$F_{MSY}$ and *B* /$B_{MSY}$ for Indian Ocean blue shark, using Scenario 2 as a reference (All CPUE estimates). Residual-mean-squared errors (RSME) represent a statistic for the goodness-of-fit, and are provided in brackets.

### *3.2.2 Swordfish CPUE fits and sensitivity*

A summary of the model fit statistics revealed that adding the extended Japanese time series in Scenario 2 slightly increased the RSME (Table 2). Compared to Scenario 2, adding the ZAF CPUE improved the goodness of the fit again as judged by the RMSE, and also helped to substantially increase the residual degrees of freedom (DF).

**Table 2**: Summary of JABBA fit statistics for Indian Ocean swordfish. $N_{obs}$: Number CPUE observations, $N_p$: Number of model parameters, DF: Residual degree of freedom, Root-mean-squared-error (RSME), Deviance Information Criterion (DIC).

| Statistic | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| $N_{obs}$ | 22 | 37 | 49 | 71 |
| $N_p$ | 8 | 8 | 10 | 12 |
| DF | 14 | 29 | 39 | 59 |
| RMSE (%) | 18 | 18.7 | 18.4 | 18.7 |
| DIC | -341 | -336.9 | -192.2 | -208.4 |

Graphical JABBA residual diagnostics for all four scenarios are presented in Fig. 7. In particular, Scenarios 2-4 showed little evidence of a systematic residual pattern as indicated by a close to straight loess spline. By comparison, Scenario 1 indicated slight departures from zero, particular at both tails of the available CPUE time series. Scenario 2 and 3 appeared to improve the stationary stability in the residual pattern compared to Scenario 1. Including the TAI.2 CPUE series decreased the goodness fit, which points towards data conflict arising. Comparisons of observed and predicted CPUE indices for individual time series are shown in Appendix I (Figs. A3-A8).

The sensitivity analysis based on all four CPUE indices demonstrated that the stock status estimates for $B/B_{MSY}$ and $F/F_{MSY}$ were generally fairly insensitive to excluding any one CPUE series at the time (Fig. 8). Excluding the JPN.II index showed the only discernible effect, but only for the period 2000-2010 and not for the final assessment year 2015. Excluding either JNP.II or TAI.II improved the fits, again indicating data conflict between the two time series. Notably, excluding the ZAF index increased the RMSE, which can be interpreted as a stabilizing property of the ZAF CPUE (Fig. 8).

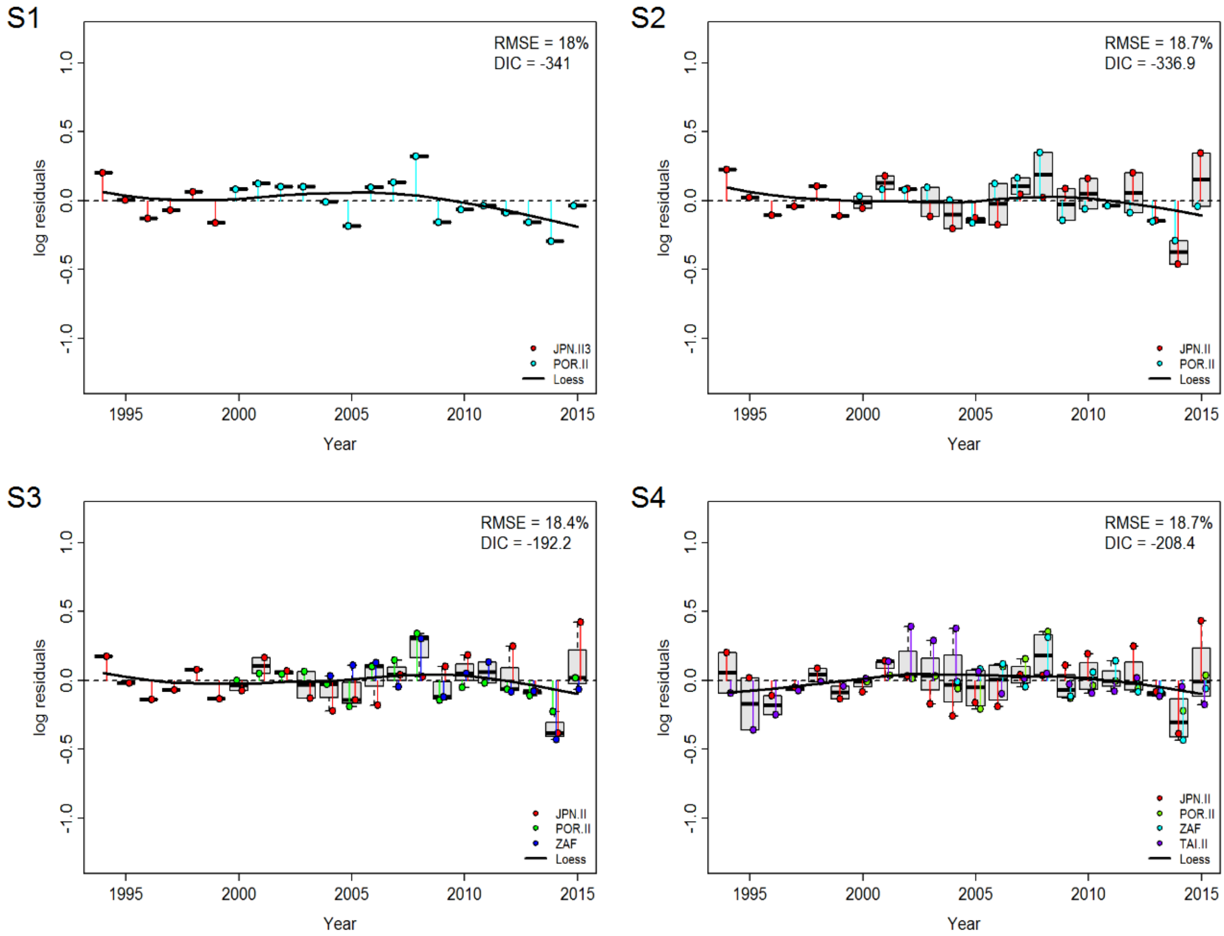


**Fig. 7.** JABBA residual diagnostic plots for the Fox model scenarios (S1-S4) for Indian Ocean swordfish showing the log-residuals for CPUE series. Loess smothers were fitted across all CPUE residuals and the width of the boxplots illustrates the relative extent of conflicts among CPUE residuals. The Residual-Mean-Error (RMSE%) is provided as a good-of-the-fit metric together with the DIC.

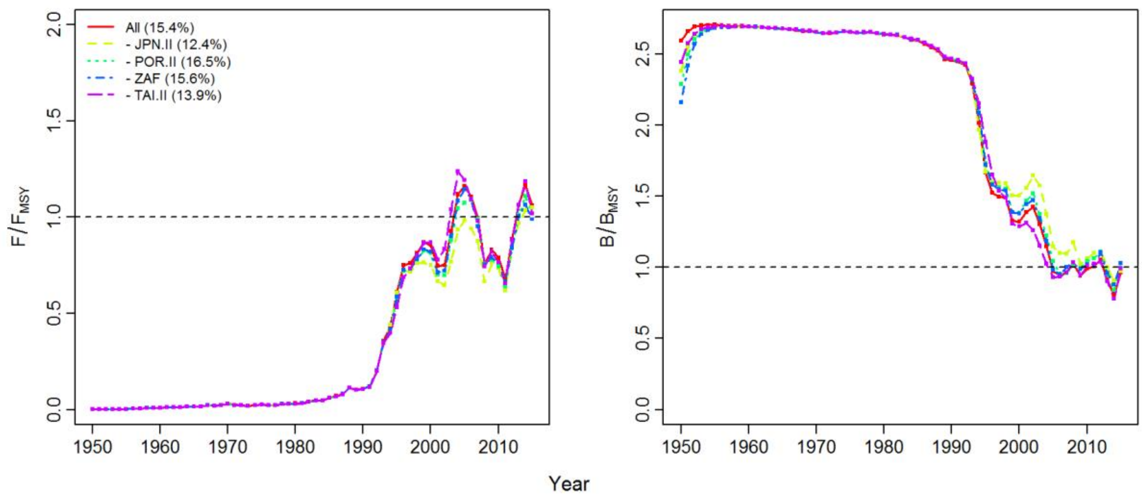


**Fig. 8.** Sensitivity analysis showing the effects of excluding one CPUE index at a time on the stock status estimates of $F/F_{MSY}$ and $B/B_{MSY}$ for Indian Ocean swordfish, using Scenario 4 as a reference (All CPUE indices). Residual-mean-squared errors (RSME) represent a statistic for the goodness-of-fit, and are provided in brackets.

### *3.3.1 Reference points and stock status for blue shark*

Model parameters, stock depletion ($B/K$) and current stock status estimates ($B$ / $B_{MSY}$ and $F$ / $F_{MSY}$) are provided for the two Schaefer model scenarios in Table 3. For the final assessment year (2015), the estimates from the two runs were similar suggesting that biomass depletion is well above $B_{MSY}$, but that current fishing mortality was either slightly below (Scenario 1) or slightly above $F_{MSY}$ (Scenario 2), respectively.

All $B$ / $B_{\mathrm{MSY}}$ trajectories predicted that although biomass has started to decrease at a faster rate since 2000, it remained well above $B_{MSY}$ until 2015. Correspondingly, fishing mortality has been increasing sharply since 2000 and is predicted to either approach $F_{\mathrm{MSY}}$ (Scenario 1) or to have marginally exceeded $F_{MSY}$ (Scenarios 2) in 2014-2015 (Fig. 9).

The extent of stock depletion and overfishing in both models are further illustrated using the Kobe plot (Figure 10). For the base-case Scenario 1, the current biomass ($B_{2015}$) is 33.3% above $B_{\mathrm{MSY}}$ and the value for current fishing mortality ($F_{2015}$) is 13.1% below $F_{MSY}$. The stock condition is predominantly in the Kobe Plot green zone with probabilities of 43-59% (Figure 10). Despite strong evidence that current biomass is above $B_{MSY}$, the current catch levels clearly exceed the stock's average surplus production (Figure 11). As such, there is increased risk of unsustainable fishing if catches continue increasing at recent rates. Future projections under constant TAC suggest that current catches in excess of 50 thousand metric tons cannot be sustained in the medium term and would need to be reduced to less than 40 thousand metric tons to maintain stock levels at around $B_{MSY}$ (Fig. 12).

**Table 3.** Summary of posterior estimates (medians) and 95% Bayesian Credibility Intervals (C.I.s) of parameters from the four JABBA scenario fits to Indian Ocean blue shark catch and CPUE series, assuming a Schaefer production function.

| | Scenario 1 | | | Scenario 2 | | |
|---|---|---|---|---|---|---|
| Estimates | Median | 2.50% | 97.50% | Median | 2.50% | 97.50% |
| $K$ | 663234.5 | 461036.2 | 1239944.0 | 582298.4 | 431406.2 | 853830.1 |
| $r$ | 0.270 | 0.234 | 0.312 | 0.272 | 0.235 | 0.314 |
| $\sigma$ | 0.07 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 |
| $F_{\mathrm{MSY}}$ | 0.135 | 0.117 | 0.156 | 0.136 | 0.117 | 0.157 |
| $B_{\mathrm{MSY}}$ | 331617.2 | 230518.1 | 619972.0 | 291149.2 | 215703.1 | 426915.0 |
| $MSY$ | 44780.9 | 31042.4 | 84566.4 | 39426.0 | 29296.8 | 58413.2 |
| $B_{1950}/K$ | 0.899 | 0.625 | 1.048 | 0.875 | 0.624 | 1.045 |
| $B_{2015}/K$ | 0.66 | 0.466 | 0.872 | 0.661 | 0.5 | 0.836 |
| $B_{2015}/B_{\mathrm{MSY}}$ | 1.319 | 0.931 | 1.743 | 1.323 | 1.000 | 1.671 |
| $F_{2015}/F_{\mathrm{MSY}}$ | 0.925 | 0.405 | 1.736 | 1.051 | 0.600 | 1.709 |

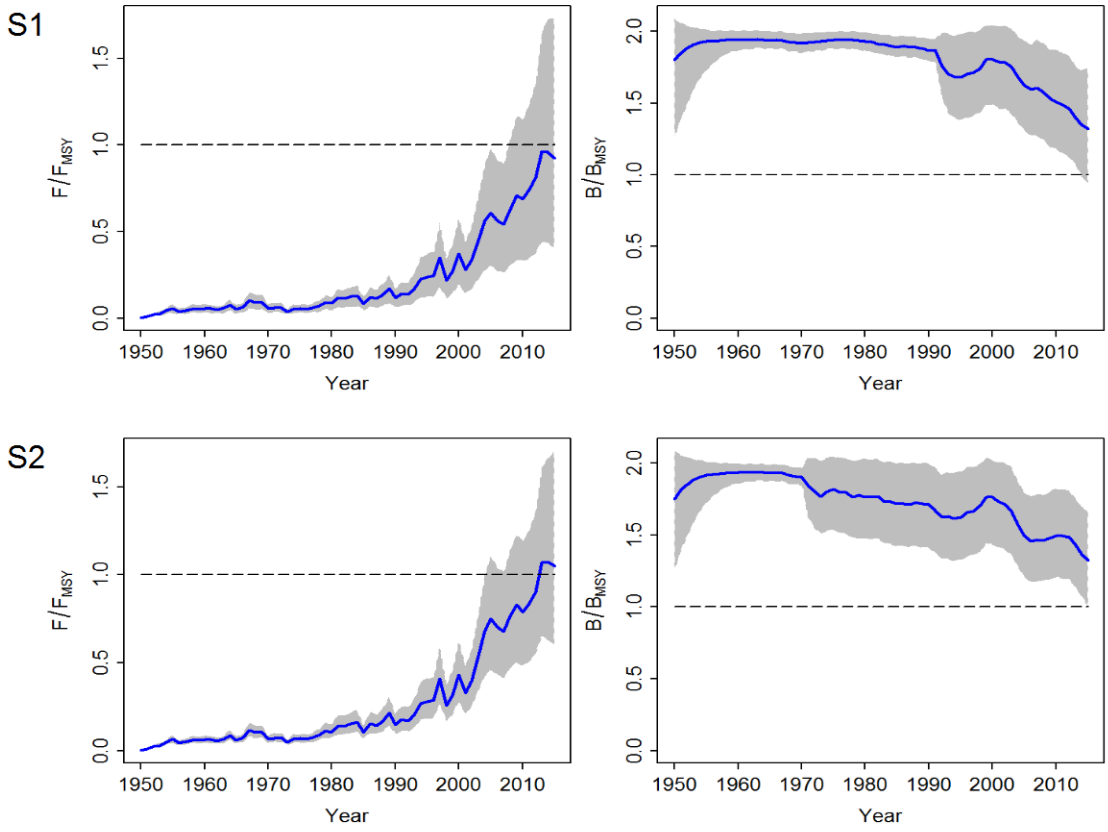


**Fig. 9.** Trajectories of $F/F_{MSY}$ and $B/B_{MSY}$ for Indian Ocean blue shark (1950-2015) for the two scenarios (S1-S2). Grey shading indicates 95% credibility intervals.

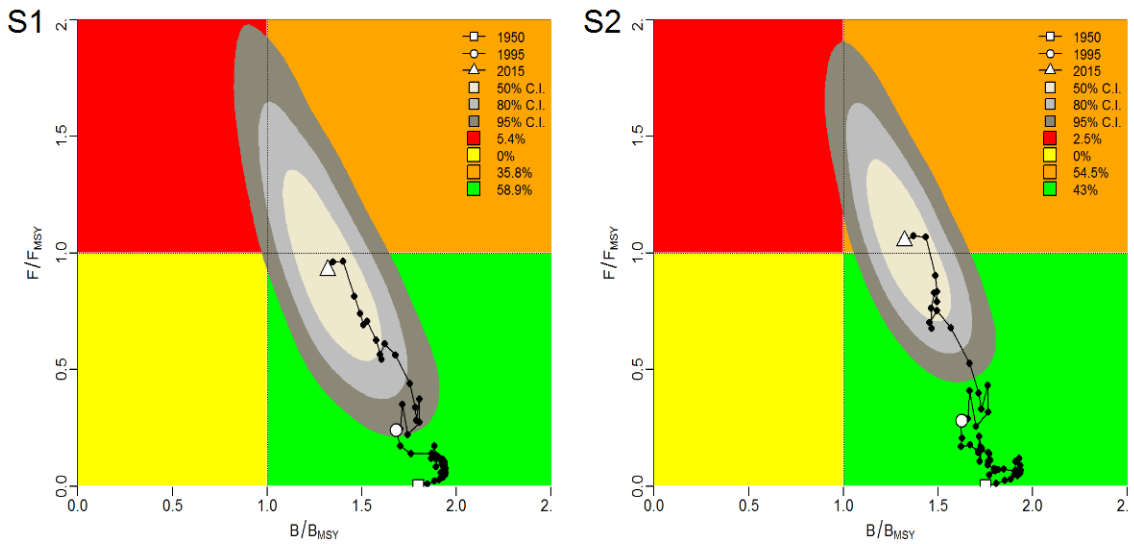


**Fig. 10.** Kobe plots for the for JABBA scenarios (S1-S2), showing the estimated trajectories (1950-2015) of $B/B_{MSY}$ and $F/F_{MSY}$ for Indian Ocean blue shark. The grey shaded areas denote the 50%, 80% and 95% credibility intervals for the final year assessment estimate. The proportion of points falling within each quadrant is indicated in the figure legend.

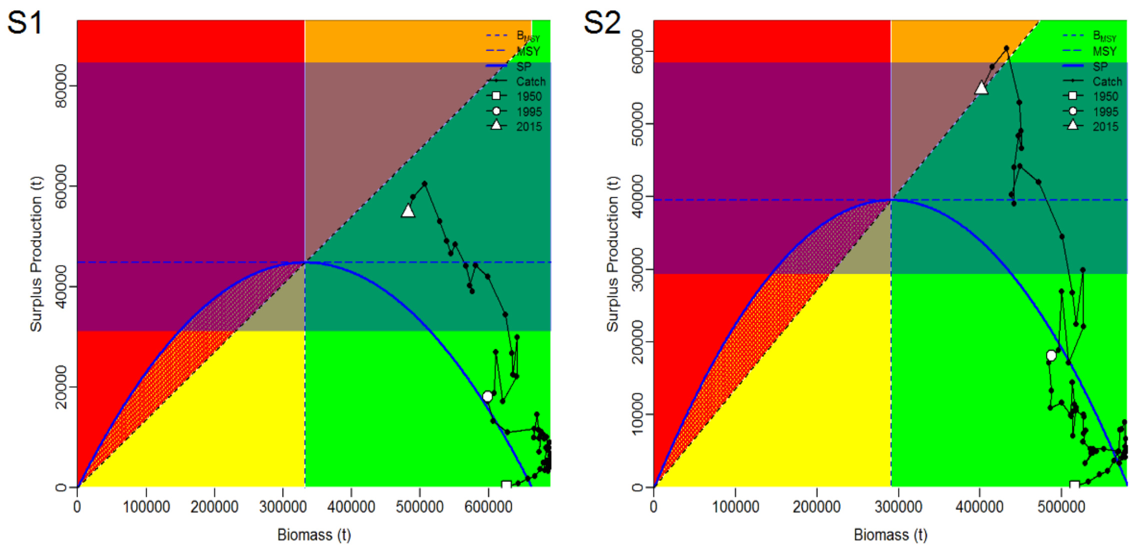


**Fig. 11.** JABBA SP-phase plot showing estimated surplus production curves and catch trajectories as a function of biomass for the Schaefer model scenarios 1-4 (S1-S4) over the period 1950-2015 for the Indian Ocean blue shark. The inflection point at MSY is highlighted together with the blue shaded area denoting its 95% credibility region. The plot background follows the color scheme of Kobe phase plot to facilitate interpretation, but additionally it superimposes plot regions (yellow dashes) where biomass can recover under a constant quota while in the red overfished state ($B<B_{MSY}$, $F > F_{MSY}$ but $SP$ > Catch).

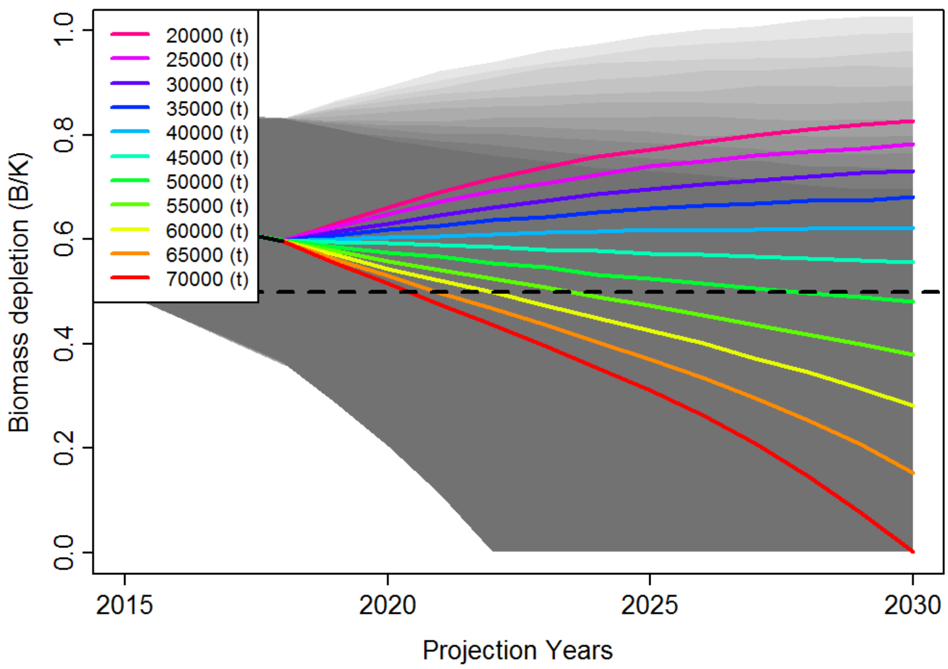


**Fig. 12.** Projections of biomass depletion based on the Schaefer model base case (Scenario 1) for Indian Ocean blue shark for various levels of future catch. The dashed line denotes $B_{MSY}$ and grey shaded areas depict the confidence regions.

### *3.3.2 Reference points and stock status for swordfish*

Model parameter, stock depletion ($B/K$) and current status estimates ($B/B_{MSY}$ and $F/F_{MSY}$) for Indian Ocean swordfish are provided for the four Fox models scenarios in Table 4. For the final assessment year (2015), all runs produced results suggesting that biomass depletion and current fishing mortality were close to $B_{MSY}$ and $F_{MSY}$, respectively. Scenario 3 and 4 are marginally more pessimistic, with medians of current fishing mortality marginally above $F_{MSY}$.

All $F/F_{\mathrm{MSY}}$ trajectories predicted that sustainable fishing mortality had been exceeded in approximately 2005 and that biomass levels had approached (Scenario 1) or dropped just below $B_{MSY}$ (Scenarios 2-4) between 2006 and 2007 (Fig. 13). The subsequent decrease in $F$ towards 2010 appears to have promoted a slight recovery in biomass. The shapes of $F/F_{\mathrm{MSY}}$ and $B/B_{MSY}$ trajectories were similar across Scenarios 1-4.

**Table 4.** Summary of posterior estimates (medians) and 95% Bayesian Credibility Intervals (C.I.s) of parameters from the four JABBA scenario fits to Indian Ocean swordfish catch and CPUE series, assuming a Fox production function.

| | Scenario 1 | | | Scenario 2 | | |
|---|---|---|---|---|---|---|
| Estimates | Median | 2.50% | 97.50% | Median | 2.50% | 97.50% |
| $K$ | 264585.2 | 137432.1 | 507121.7 | 273653.2 | 181151.1 | 446504.7 |
| $r$ | 0.343 | 0.190 | 1.019 | 0.307 | 0.187 | 0.479 |
| $\psi$ (*psi*) | 0.875 | 0.598 | 1.084 | 0.89 | 0.581 | 1.051 |
| $\sigma$ | 0.06 | 0.032 | 0.089 | 0.055 | 0.032 | 0.089 |
| $F_{\mathrm{MSY}}$ | 0.343 | 0.189 | 1.018 | 0.306 | 0.186 | 0.478 |
| $B_{\mathrm{MSY}}$ | 97384.1 | 50583.7 | 186652.9 | 100721.7 | 66675.1 | 164342.0 |
| *MSY* | 31476.4 | 25731.7 | 81952.1 | 30389.9 | 26246.5 | 41238.6 |
| $B_{1950}/K$ | 0.875 | 0.598 | 1.082 | 0.89 | 0.581 | 1.05 |
| $B_{2015}/K$ | 0.467 | 0.229 | 0.866 | 0.431 | 0.301 | 0.653 |
| $B_{2015}/B_{\mathrm{MSY}}$ | 1.270 | 0.622 | 2.352 | 1.172 | 0.819 | 1.774 |
| $F_{2015}/F_{\mathrm{MSY}}$ | 0.809 | 0.169 | 1.851 | 0.911 | 0.452 | 1.414 |
| | Scenario 3 | | | Scenario 4 | | |
| Estimates | Median | 2.50% | 97.50% | Median | 2.50% | 97.50% |
| $K$ | 272164.9 | 185400.1 | 423862.5 | 255764.8 | 169530.1 | 392495.7 |
| $r$ | 0.294 | 0.176 | 0.464 | 0.313 | 0.190 | 0.493 |
| $\psi$ (*psi*) | 0.825 | 0.54 | 1.038 | 0.855 | 0.617 | 1.047 |
| $\sigma$ | 0.06 | 0.032 | 0.095 | 0.055 | 0.032 | 0.095 |
| $F_{\mathrm{MSY}}$ | 0.294 | 0.176 | 0.463 | 0.313 | 0.19 | 0.493 |
| $B_{\mathrm{MSY}}$ | 100173.9 | 68239.0 | 156008.2 | 94137.6 | 62397.8 | 144463.3 |
| *MSY* | 29282.2 | 25005.6 | 35493.1 | 29380.3 | 25436.4 | 34652.8 |
| $B_{1950}/K$ | 0.825 | 0.54 | 1.037 | 0.856 | 0.617 | 1.046 |
| $B_{2015}/K$ | 0.377 | 0.264 | 0.549 | 0.377 | 0.265 | 0.523 |
| $B_{2015}/B_{\mathrm{MSY}}$ | 1.023 | 0.717 | 1.492 | 1.024 | 0.720 | 1.420 |
| $F_{2015}/F_{\mathrm{MSY}}$ | 1.080 | 0.625 | 1.650 | 1.078 | 0.678 | 1.611 |

The extent of stock depletion ($B/B_{MSY}$) and overfishing ($F/F_{MSY}$) is further illustrated in the form of Kobe phase plots for all four scenarios (Fig. 14). The probability of the stock being in the sustainable (target) area ranged from 35.8% (Scenario 4) to 65.3% (Scenario 2). In contrast, the risk of the stock being overfished ranged from 20.0% (Scenario 2) to 44.6% (Scenario 4). Scenario 3 and 4 produced slightly more pessimistic estimates about the stock status but no Scenario predicted more than a 50% probability of being in an overfished state. Comparisons of the stock status posteriors highlight the increased uncertainty associated with Scenario 1, which results in an increased risk of overfishing compared to Scenario 2 despite very similar point estimates of $B/B_{MSY}$ and $F/F_{MSY}$.

All four scenarios predicted that the majority of swordfish catches have remained under the surplus production since 2010 (Fig. 16). However, results from the most recent years suggest that the catch has already exceeded surplus production levels. Median estimates of MSY were similar and ranged from 29 282 to 31 476 metric tons. By adding further abundance information to Scenario 1, the uncertainty around the MSY estimates could be substantially decreased for Scenarios 2-4 (Table 4; Fig. 15).

Overall, the mean stock status estimates are comparable across all 4 scenarios. However, considering only the short JPN.II3 (94-99) and the EU-POR (2000-2015) CPUE series for Scenario1 resulted in very high uncertainty about the stock status. Adding the extended JPN.II time series (1994-2015) alone to Scenario 2 reduced the uncertainty about the stock status substantially, without introducing apparent data conflict. Including the ZAF CPUE in Scenario 3 generally corroborated the trends and produced satisfying fitting diagnostics. Finally, adding the recent TAI.II (1994-2015) further corroborated the stock status, but appears to introduce some degree of data conflict with the JPN.II data. Taking trade-offs among goodness of the fits, precision and residual degrees of freedom as an indicator for predictive power into account, Scenario 3 appears the most plausible candidate base-case scenario, closely followed by Scenario 2. According to projections from Scenario 3, total catch levels should be kept at least below 28 000 metric tons to maintain sustainable biomass levels into the future (Fig .16).

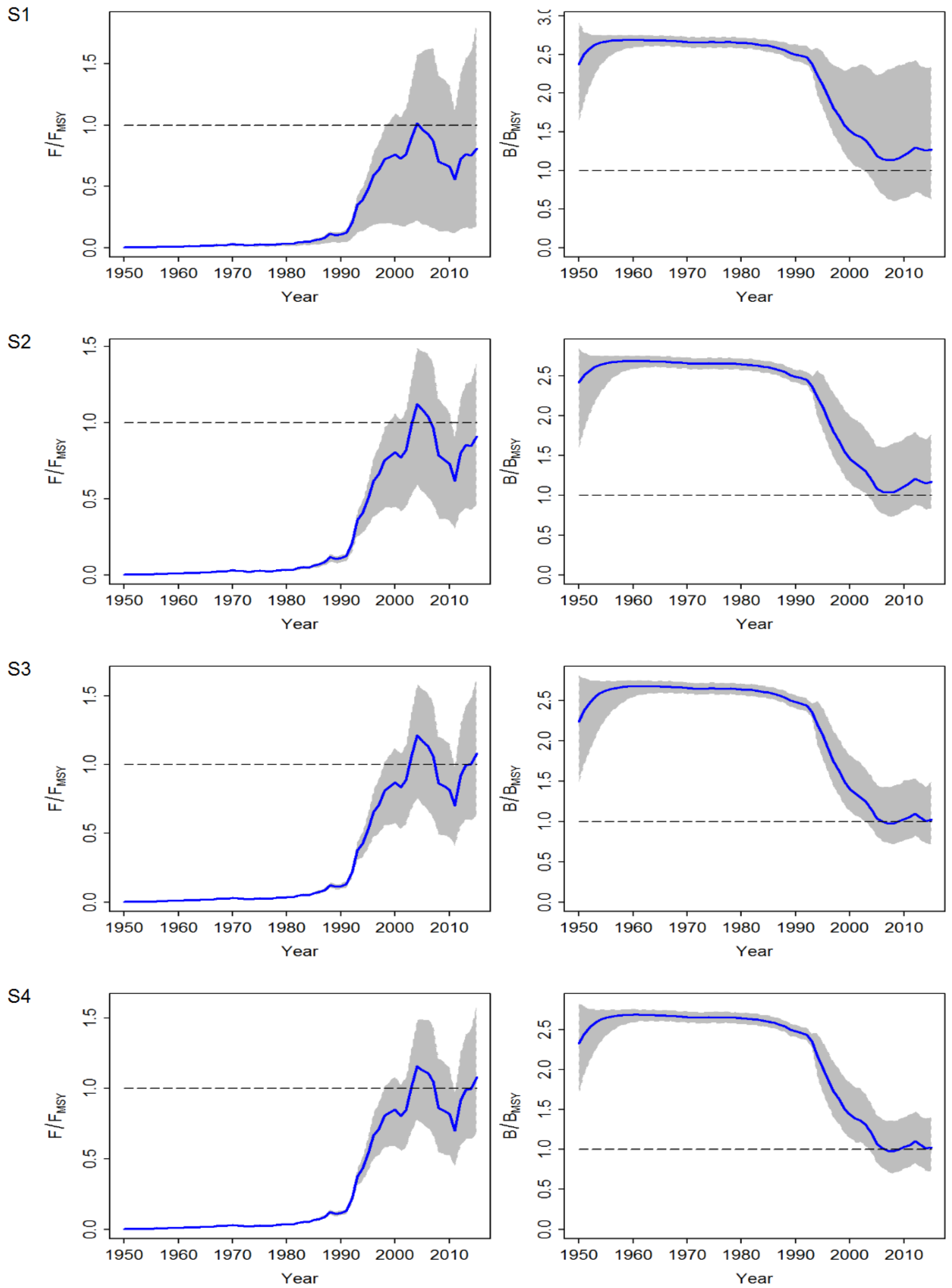


**Fig. 13.** Trajectories of $F/F_{MSY}$ and $B/B_{MSY}$ for Indian Ocean swordfish (1950-2015) for the four scenarios (S1-S4). Grey shading indicates 95% credibility intervals.

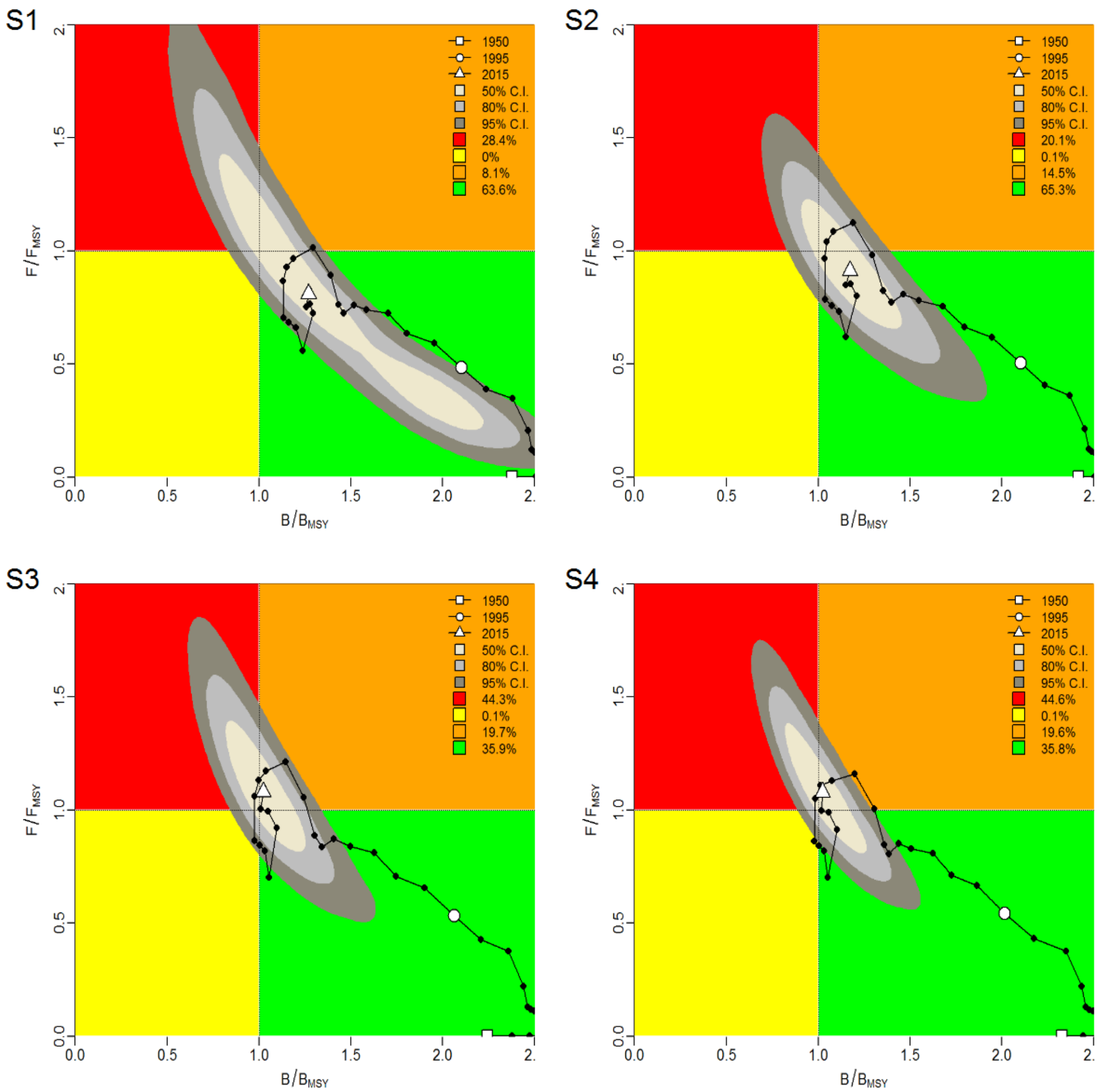


**Fig. 14.** Kobe plots for the for JABBA scenarios (S1-S4), showing the estimated trajectories (1950-2015) of $B/B_{MSY}$ and $F/F_{MSY}$ considered for the Indian Ocean swordfish stock assessment. Different grey shaded areas denote the 50%, 80% and 95% credibility interval for the final assessment years. The percentage of run estimates falling within each quadrant is indicated in the figure legend.

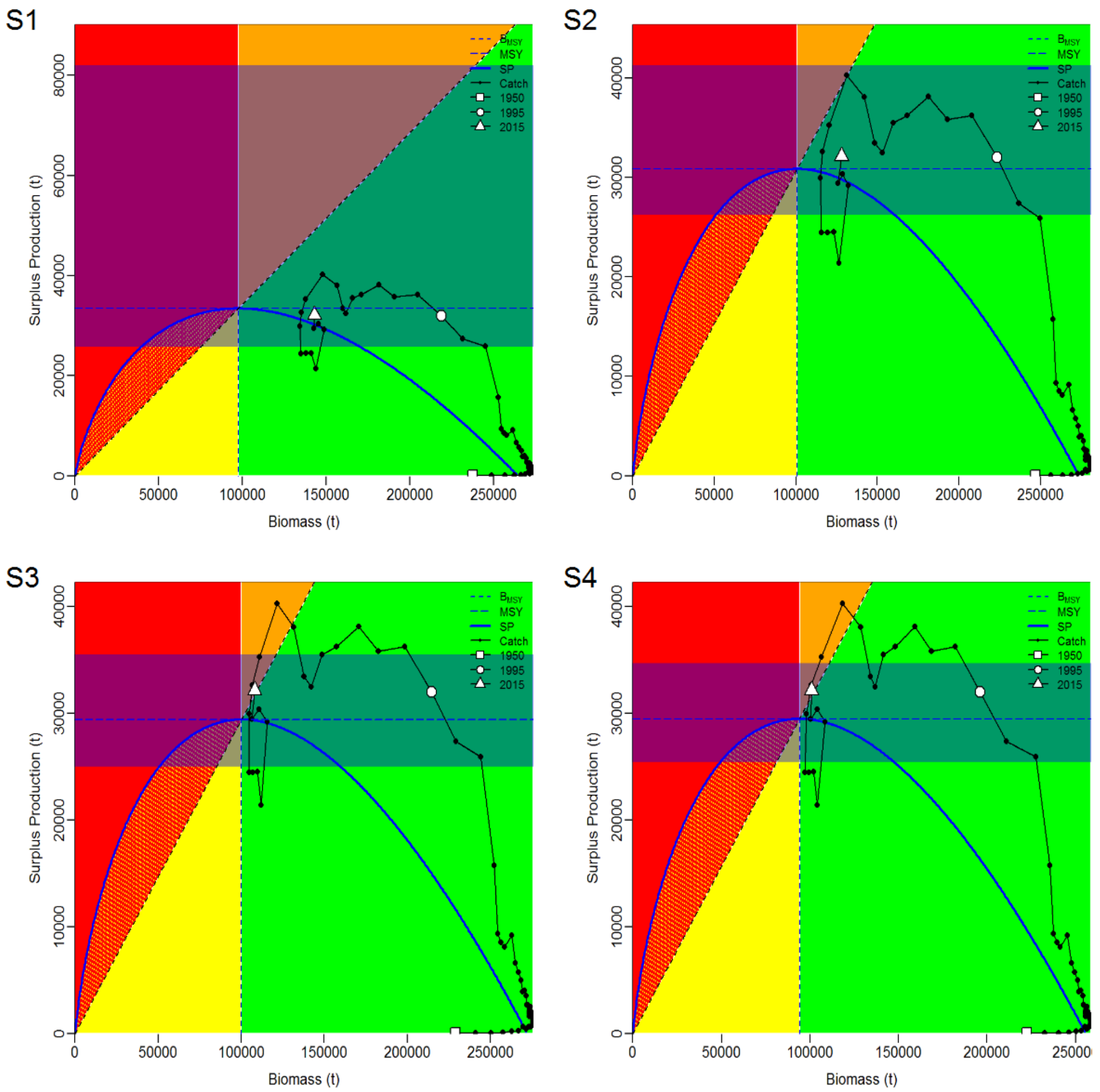


**Figure 15.** JABBA SP-phase plot showing estimated surplus production curves and catch trajectories as a function of biomass shown for Fox model scenarios 1-4 (S1-S4) over the period 1950-2015 for the Indian Ocean swordfish. The inflection point at MSY is highlighted together with the blue shaded area denoting its 95% credibility region. The plot background follows the color scheme of Kobe phase plot to facilitate interpretation, but additionally it superimposes plot regions (yellow dashes) where biomass can recover under a constant quota while in the red overfished state ($B<B_{MSY}$, $F > F_{MSY}$ but $SP >$ Catch).

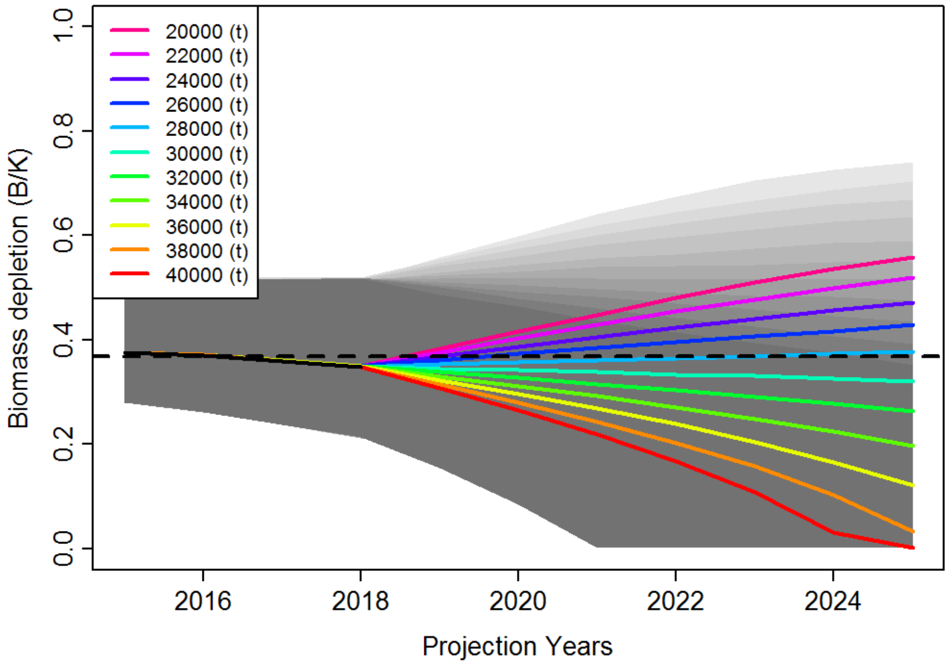


**Fig. 16.** Projections of biomass depletion based on the Fox model candidate base case (Scenario 3) for Indian Ocean swordfish for various levels of future catch. The dashed line denotes $B_{MSY}$ and grey shaded areas depict the confidence regions.

*3.4. Remarks*

We have demonstrated applications of a number of JABBA core features using the 2017 IOTC blue shark and swordfish assessments as working examples. The assessment input data comprised multiple, partially conflicting, fisheries-depend abundance indices over varying time spans, as commonly encountered in assessments of large pelagic fishes. We demonstrated how the inbuilt fit diagnostics can be applied to identify conflicting abundance indices and improve the identification of candidate base-case scenarios. The selected base-case scenarios were used to infer the current stock status and make future projections under varying catch quotas.

A strength of JABBA is that it allows a large number of alternative scenarios, including readily presentable diagnostic and output graphs, to be produced relatively quickly. All assessment scenarios presented here can be reproduced in less than 15 min (~ 150 seconds per run). This allows quick manipulation and testing to be carried out on models using alternative input data or model specifications. As such, JABBA is lends itself to time-constrained RFMO assessment meetings.

## 4. References

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Meyer, R., Millar, C.P., 1999. BUGS in Bayesian stock assessments. Can. J. Fish. Aquat. Sci. 56, 1078–1086.

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## Appendix A

*Indian Ocean blue shark fits*

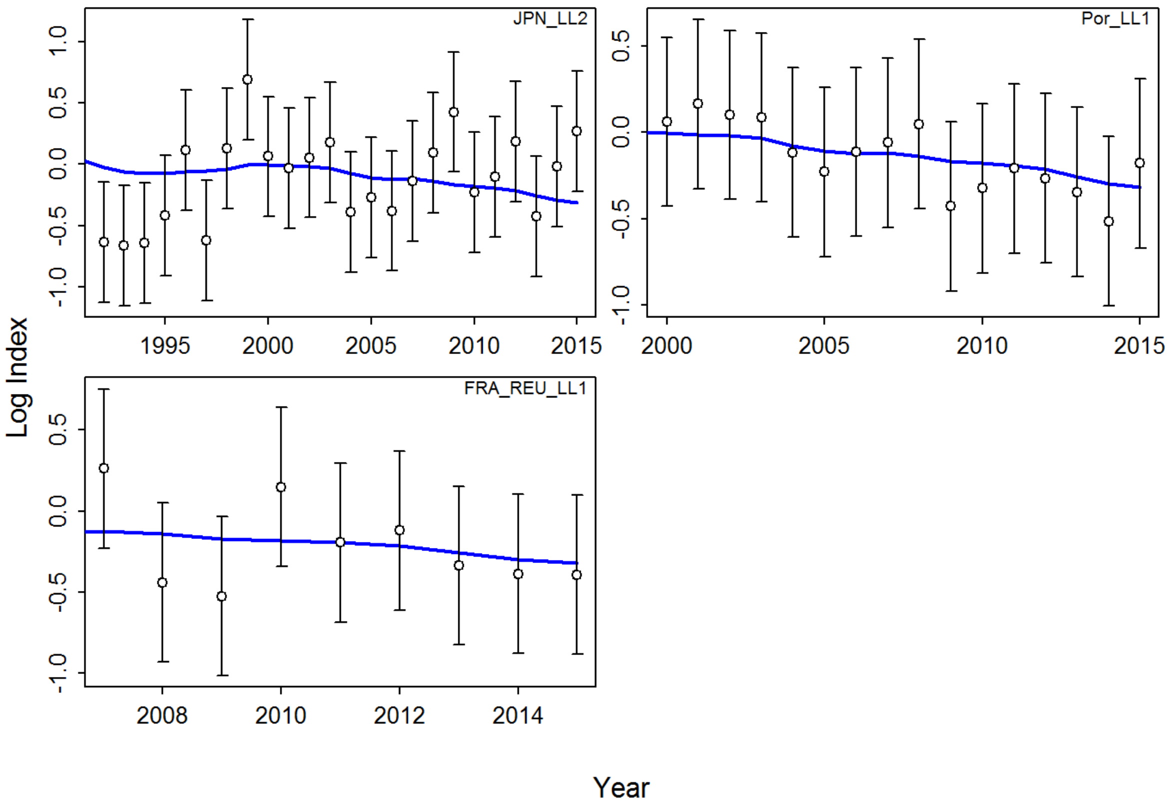


**Fig. A1.** Observed and predicted CPUE based on the fit for Scenario 1 for Indian Ocean blue shark.

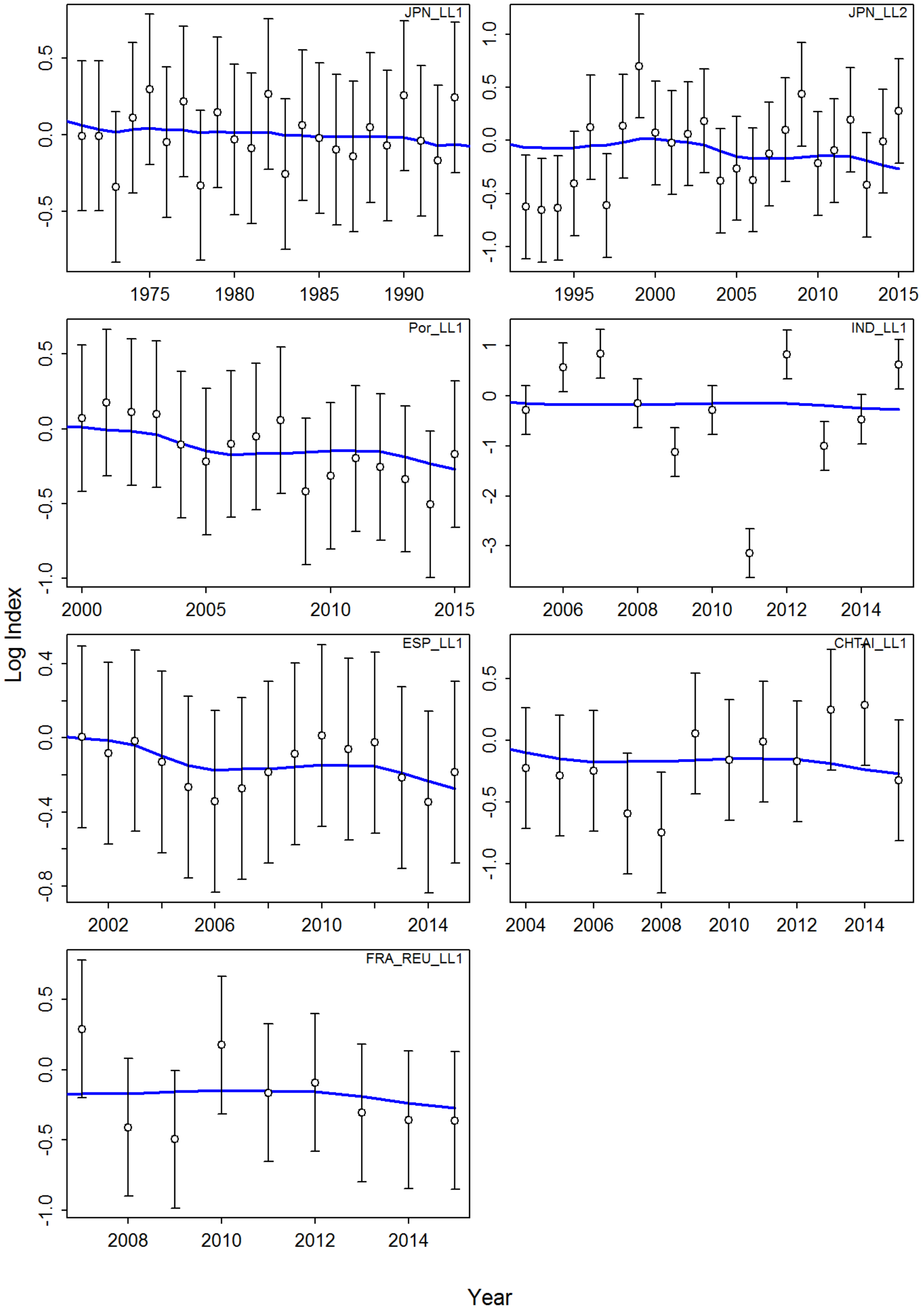


**Fig. A2.** Observed and predicted CPUE based on the fit for Scenario 2 for Indian Ocean blue shark.

*Indian Ocean swordfish fits*

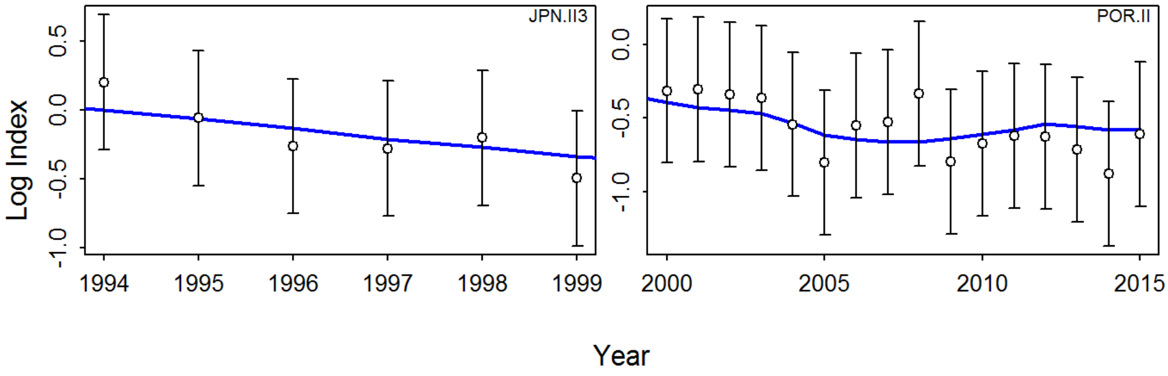


**Fig. A3.** Observed and predicted CPUE based on the fit for Scenario 1 for Indian Ocean swordfish.

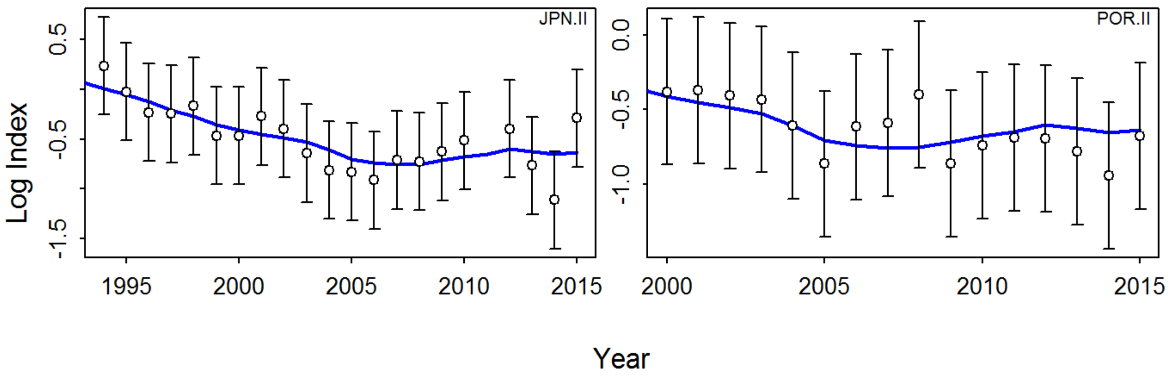


**Fig. A4.** Observed and predicted CPUE based on the fit for Scenario 2 for Indian Ocean swordfish.

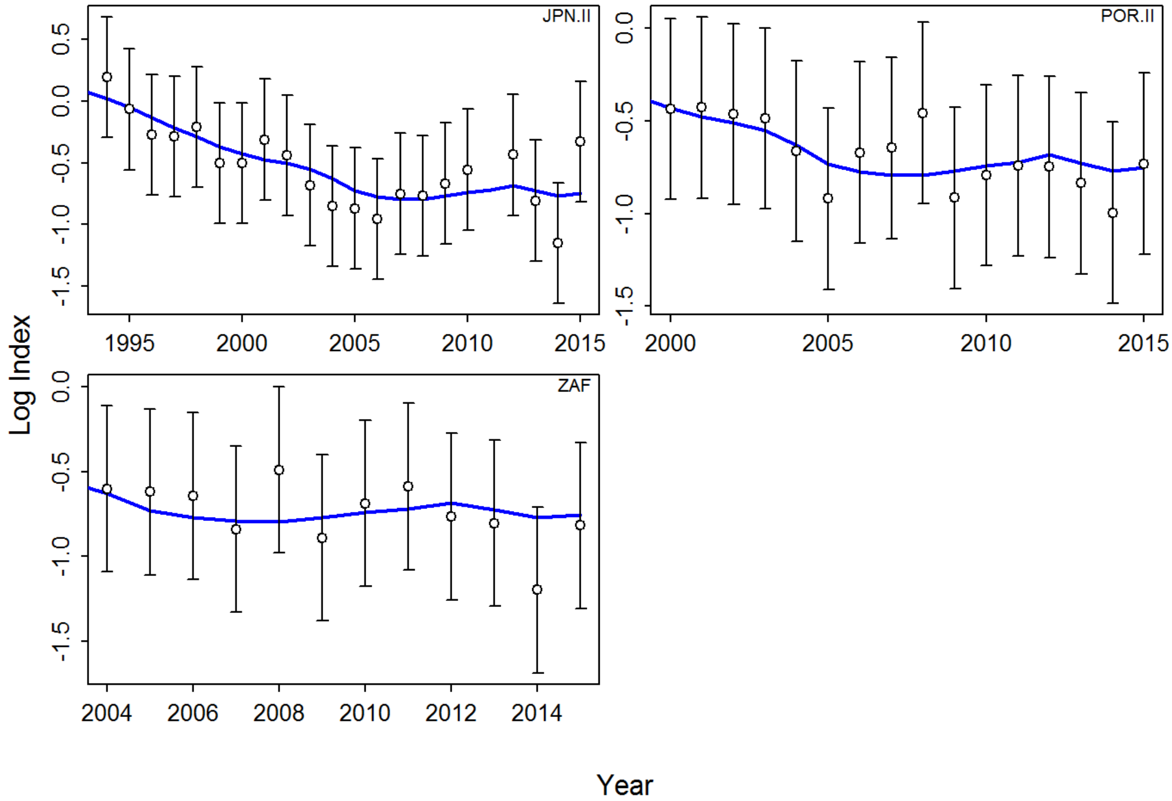


**Fig. A5.** Observed and predicted CPUE based on the fit for Scenario 3 for Indian Ocean swordfish.

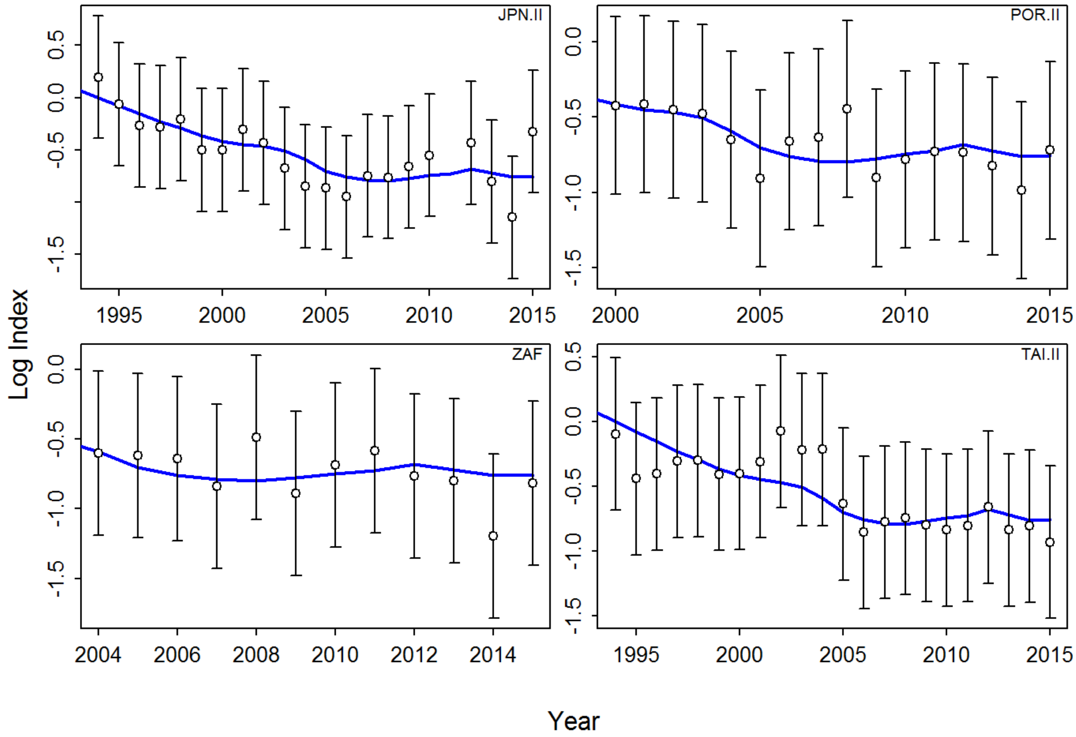


**Fig. A6.** Observed and predicted CPUE based on the fit for Scenario 4 for Indian Ocean swordfish.