BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL *JABBA* ASSESSMENT OF INDIAN OCEAN STRIPED MARLIN (*TETRAPTURUS AUDAX*) STOCK

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SUMMARY

Five scenarios were run using Bayesian State-Space Surplus Production Models to assess the Indian Ocean striped marlin (*Tetrapturus audax*) using the open-source stock assessment tool JABBA. A 'drop one' sensitivity analysis indicated that omitting any of the CPUE time-series would not significantly alter the stock status. Similarly, a retrospective analysis produced highly consistent results for stock status estimates back to 2007 and therefore provided no evidence for an undesirable retrospective pattern. As such, all CPUE time-series were used for scenarios 1-4 in this assessment, and the historical Japan CPUE was omitted in scenario 5 for comparison with ss3 model runs. The results for the five alternative scenarios estimated MSY between 4,549 and 4,950 tons. Median estimates of B/B_{MSY} from the five scenarios ranged between 0.28 - 0.38 and B/K between 0.09 - 0.11. All scenarios produce B/B_{MSY} trajectories that steadily declined from the late 1970s to 2010 before leveling at the approximate current B/B_{MSY} estimates. However, a steady increase of F/F_{MSY} since the 1970s has continued unabated. Individual Kobe biplots were similar among all scenarios and each indicated a >99% probability that the Indian Ocean striped marlin stock is overfished and subject to overfishing - these results are comparable with the 2017 assessment for this species. Scenario five (S5) was determined to be the Base Case scenario. The robustness to the retrospective analysis results provides a degree of confidence in the predictive capabilities of the assessment and, therefore, the model's ability to inform management decisions by means of future projections under alternative quota.

KEY WORDS

Stock status, CPUE fits, diagnostics, process error, stochastic biomass dynamics

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1. Introduction

In 2017, the Indian Ocean Commission (IOTC) carried out an assessment for striped marlin (*Tetrapturus audax*) using four different model types; Stock Reduction Analysis (SRA), the Surplus Production Models (SPMs) ASPIC without process error, a Bayesian State Space Production Model (SSBSP) with process error, and the statistical age-structured model Stock Synthesis (ss3). The assessment comprised catch and effort data through 2015 and estimations of management reference points (IOTC, 2017). Results for all models included in the 2017 assessment were consistent in indicating that the stock has been subject to overfishing in the last two decades. As a result, the stock biomass is well below the B_{MSY} level. On the weight-of-evidence available in 2017, the stock status of striped marlin is determined to be *overfished* and *subject to overfishing*. Projections from all the models show that there is a very high risk of remaining in overfished status unless catches are substantially decreased.

Here we provide an updated assessment of the Indian Ocean striped marlin stock based on the Bayesian State-Space Surplus Production Model software 'JABBA' (Winker et al. 2018a; Just Another Bayesian Biomass Assessment). JABBA is implemented as a flexible, user-friendly open-source tool that is hosted on GitHub (https://github.com/jabbamodel) that has been applied in a number of recent ICCAT stock assessments, including the billfish assessments of South Atlantic swordfish (ICCAT, 2017; Winker et al., 2018a) and Atlantic blue marlin (Mourato et al., 2018). Model diagnostics are presented in the form of sensitivity analysis, retrospective analysis and prior vs posterior plots. Details of the JABBA model results for five alternative scenarios are discussed in terms of robustness and inference about the stock status.

2. Material and Methods

2.1. *Fishery input data*

Total nominal catch by fleet was obtained from the IOTC Secretariat in preparation to assess the Indian Ocean striped marlin at WPB16. Two differing nominal catch scenarios were proposed: *IOTC-2018-WPB16-DATA12a_Rev1_-_SA_MLS* and *IOTC-2018-WPB16-DATA12b_-_SA_MLS*. Both of these catch time-series spanned from 1950 to 2017, with the former providing a continuity run from the 2017 striped marlin assessments. Relative abundance indices were made available in the form of standardized catch-per-unit-of-effort (CPUE) time-series, which were assumed to be proportional to biomass. The standardized CPUE series covered two fishing fleets, Japan and Taiwan,China (Table 1). For this assessment, the selected CPUE indices were spatially limited to the northern Indian Ocean, representative of the North-East and North-West regions. Furthermore, the Japanese CPUE time-series was provided separately for the periods 1976- 1993 and 1994-2017, where the 1994-2017 CPUE represented an update compared to the 2017 assessment. This resulted in a total of six standardized CPUE series (Table 1).

2.2. *JABBA stock assessment model*

This initial stock assessment was implemented using the Bayesian state-space surplus production model framework JABBA, version v1.2 (Winker et al., 2018a). 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 the shape parameter *m*. A full description of the JABBA model, including formulation and state-space implementation, prior specification options and diagnostic tools is available in Winker et al. (2018a).

To assess striped marlin, we considered five alternative specifications of the Pella-Tomlinson model type based on two differing nominal catch data time-series, two differing CPUE time-series combinations and three differing *r* priors and associated input values of B_{MSY}/K. The input priors were objectively derived from the ASEM simulations (Winker et al. 2008b; Winker et al. 2018c), which allowed approximating the parameterizations considered for age-structured stock synthesis model (ss3) based on range of stock recruitment steepness values for the stock recruitment relationship (h = 0.4, h = 0.5 and h = 0.86), while admitting reasonable uncertainty about the natural mortality *M*. As a reference case, we chose the *r* prior associated with B_{MSY}/K = 0.37 (h = 0.5) to approximate the Fox model parameterization used in the 2017 assessment (Winker et al. 2018c). In addition, we ran a scenario with a *r* prior that corresponds to high steepness value of h = 0.86 to match the reference case assumption for the 2017 SS3 assessment model, while low resilience prior formulation was based on h = 0.4 (Table 2). This resulted in the formulation of the following five scenario specifications:

- **S1 (Cont.):** for B_{MSY}/K = 0.37 (h = 0.5), *r* prior *LN* ~ (log (0.25), 0.15)), catch data = Data 12a, including all CPUE time-series.

- **S2 (Ref.):** for B_{MSY}/K = 0.37 (h = 0.5), *r* prior *LN* ~ (log (0.25), 0.15)), catch data = Data 12b, including all CPUE time-series.

- **S3:** for B_{MSY}/K = 0.4 (h = 0.4), *r* prior *LN* ~ (log (0.21), 0.14)), catch data = Data 12b, including all CPUE time-series.

- **S4:** for B_{MSY}/K = 0.23 (h = 0.86), *r* prior *LN* ~ (log (0.31), 0.16)), catch data = Data 12b, including all CPUE time-series.

- **S5:** for B_{MSY}/K = 0.37 (h = 0.5), *r* prior *LN* ~ (log (0.25), 0.15)), catch data = Data 12b, omit both Japan historical CPUE time-series (JPN_NW_hist and JPN_NE_hist).

For *K*, we assumed a vaguely informative lognormal prior with a mean 50,000 metric tons and CV of 300%. Initial depletion was estimated using a lognormal prior ($\varphi = B_{1950}/K$; for details see Winker et al., 2018a) with mean = 1 and CV of 10%. All catchability parameters were formulated as uninformative uniform priors, while the observation variance was implemented by assuming inverse-gamma priors. Initial trials indicated that estimating the process error (sigma) resulted in large variance estimates that would result implausible large variations in annual stock biomass. Instead, the process error was therefore fixed at 0.07 (see Ono et al., 2012 for details).

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. 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, two 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 (1992), Geweke (1992) and Gelman and Rubin (1992) diagnostics as implemented in the coda package.

To assess the relative influence of individual CPUE time-series on the stock status estimates for the Reference Case (S2) we ran a sensitivity analysis by iteratively removing a single CPUE time-series and comparing the predicted vectors of biomass B_y, fishing mortality F_y, the ratios B_y/K, B_y/B_{MSY} and F_y/F_{MSY} and the sensitivity of the surplus production function. To further evaluate the robustness of important stock status quantities (biomass, surplus production, B/B_{MSY} and F/F_{MSY}) for use in projections, we conducted a retrospective analysis (Mohn, 1999) for the Reference Case S2 by sequentially removing the most the recent year (retrospective 'peel') and refitting the model over a period of ten years (i.e. 2017 back to 2007).

3. Results and Discussion

Nominal catches of striped marlin in the Indian Ocean were highly variable, peaking in 1987 with a total of 8,729 tons for both available time-series (Figure 1) - the data from the two time-series only differs from 2000 onward. Fits were generally comparable among all five scenarios (Figures 2 & 3), which was also supported by the narrow range RMSE values (RMSE = 47.5-48.3%), suggesting that the goodness-of-fits were very similar. For both Taiwan,China CPUE indices (NW and NW) the predicted CPUE showed a good fit to the observed CPUEs and these are seemingly more informative to the model than that of the Japanese indices (Figure 4). However, the model fails to fully describe the sharp initial decline in observed historical Japanese CPUE between the late 1970s and early 1980s, which resulted in some moderate data conflicts and were subsequently omitted in scenario 5. In general, all CPUE indices were consistent in showing an extended period of decline from the 1970s until attaining a minimum around 2010.

The ‘drop one’ sensitivity analysis indicates that omitting the Taiwan,China NW index would result in a more pessimistic assessment outcome, while the omission of either the Taiwan,China and/or the Japanese NE indices would produce a more optimistic assessment result in terms of B/B_{MSY} and F/F_{MSY} (Figure 4). However, none of these deviations would significantly alter the stock status as the most optimistic sensitivity estimate for B/B_{MSY} remains well below 1. The retrospective analysis produced highly consistent stock status estimates back to 2007, showing only negligible departures of retrospective peel from the reference predictions through to 2017. There was therefore no evidence for an undesirable retrospective pattern.

The MSY estimates showed little variation, ranging between 4,549 and 4,950 tons for all five scenarios (Table 3). In contrast, B_{MSY} varied substantially among scenarios, with S4 (9,796 t) being approximately a third of that estimated from S3 (26,847 t). Estimates of B_{MSY} from S1, S2 and S5 were more comparable (18,020, 18,130 t and 17,935, respectively). The F/F_{MSY} estimates ranged between 1.81 and 2.93 for S4 and S1, respectively. The range of median estimates for B/B_{MSY} from the five scenarios was 0.28 - 0.38 and the range for *B/K* median estimates was 0.09 - 0.11 (Table 3).

All scenarios produce B/B_{MSY} trajectories that steadily declined from the late 1970s to around 2010 before leveling at the approximate current B/B_{MSY} estimates. However, a steady increase of F/F_{MSY} since the 1970s has continued unabated. Individual Kobe biplots were similar among all scenarios and each indicated a >99% probability that the Indian Ocean striped marlin stock is overfished and currently subjected to overfishing (Figure 10). Similarly, a combined Kobe posterior plot for all scenarios indicates a 99.8% probability the stock is overfished and subject to overfishing (Figure 11). A characteristic of Kobe biplots depicting depleted stocks is evident in this assessment in that there is high uncertainty in F/F_{MSY} estimates and relatively high confidence in the B/B_{MSY} estimates.

The results of this initial JABBA assessment are broadly comparable with the 2017 assessment for the Indian Ocean striped marlin stock, suggesting that the stock remains *overfished* and *subject to overfishing*. The robustness to the retrospective analysis results provides a degree of confidence in the predictive capabilities of the assessment and, therefore, the assessments ability to inform management decisions by means of future projections under alternative quota.

4. References

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Table 1. Summary of catch-per-unit-effort (CPUE) indices considered in the 2018 JABBA assessment runs for Indian Ocean striped marlin.

CPUE indices and period	Period	Abbreviation
Taiwan,China North-West Indian Ocean	1979-2017	TWN_NW
Taiwan,China North-East Indian Ocean	1979-2017	TWN_NE
Japan North-West Indian Ocean	1976-1993	JPN_NW_hist
Japan North-East Indian Ocean	1976-1993	JPN_NE_hist
Japan North-West Indian Ocean	1994-2010	JPN_NW
Japan North-East Indian Ocean	1994-2017	JPN_NE

Table 2. Summary of prior and input parameter assumptions used in the 2018 JABBA Indian Ocean striped marlin assessment. (ref *h*): Reference case corresponding to a Beverton and Holt stock-recruitment steepness parameter of h = 0.5 and B_{MSY}/K ratio of a Fox Surplus Production model; (low *h*): lower *r* run corresponding to h = 0.4; (high *h*): higher *r* run corresponding to h = 0.86 (see Winker et al. 2018c).

Parameter	Description	Prior	*m*	CV	Scenario
K	Unfished biomass	lognormal	50,000	300%	All
r (ref *h*)	Population growth rate	lognormal	0.25	14%	S1, S2, S5
r (low *h*)		lognormal	0.14	15%	S3
r (high *h*)		lognormal	0.31	16%	S4
ψ (*psi*)	Initial depletion	lognormal	1	10%	All
s^2 *(proc)*	Process error variance	fixed	0.7	-	All
B_{MSY}/K (ref *h*)	Ratio Biomass at MSY to *K*	fixed	0.37	-	S1, S2, S5
B_{MSY}/K (low *h*)		fixed	0.4	-	S3
B_{MSY}/K (high *h*)		fixed	0.23	-	S4

Table 3. Summary of posterior quantiles denoting the 95% credibility intervals of parameters estimates for five initial JABBA scenarios for Indian Ocean striped marlin.

	Scenario 1 (Cont.)			Scenario 2 (Ref.)		
Estimates	**Median**	**2.50%**	**97.50%**	**Median**	**2.50%**	**97.50%**
K	52144	42250	66828	52356	42367	64849
r	0.26	0.20	0.32	0.26	0.21	0.32
y (*psi*)	0.97	0.81	1.14	0.97	0.81	1.14
σ_{proc}	0.07	0.07	0.07	0.07	0.07	0.07
m	1.01	1.01	1.01	1.01	1.01	1.01
F_{MSY}	0.25	0.20	0.32	0.25	0.20	0.32
B_{MSY}	19297	15636	24732	19376	15679	23999
MSY	4921	4469	5364	4898	4448	5377
B_{1950}/K	0.96	0.78	1.12	0.96	0.77	1.12
B_{2017}/K	0.10	0.06	0.17	0.11	0.06	0.19
$B_{2017}/B_{\mathrm{MSY}}$	0.27	0.15	0.45	0.29	0.17	0.50
$F_{2017}/F_{\mathrm{MSY}}$	3.04	1.86	5.53	2.14	1.27	3.78
	Scenario 3 (low h)			**Scenario 4 (high h)**		
Estimates	**Median**	**2.50%**	**97.50%**	**Median**	**2.50%**	**97.50%**
K	67121	53759	84883	42622	35931	50102
r	0.21	0.17	0.27	0.20	0.17	0.25
y (*psi*)	0.97	0.81	1.14	0.97	0.81	1.13
σ_{proc}	0.07	0.07	0.07	0.07	0.07	0.07
m	1.19	1.19	1.19	0.44	0.44	0.44
F_{MSY}	0.18	0.14	0.23	0.46	0.39	0.56
B_{MSY}	26847.1	21502.7	33951.5	9796.2	8258.4	11515.3
MSY	4816.9	4261.1	5419.5	4550.2	4261.1	4806.3
B_{1950}/K	0.96	0.77	1.12	0.96	0.77	1.12
B_{2017}/K	0.11	0.06	0.18	0.09	0.05	0.14
$B_{2017}/B_{\mathrm{MSY}}$	0.28	0.16	0.45	0.39	0.21	0.62
$F_{2017}/F_{\mathrm{MSY}}$	2.27	1.42	4.03	1.73	1.09	3.17
	Scenario 5 (Base Case)					
Estimates	**Median**	**2.50%**	**97.50%**			
K	48464	38416	62500			
r	0.27	0.20	0.34			
y (*psi*)	0.97	0.81	1.14			
σ_{proc}	0.07	0.07	0.07			
m	1.01	1.01	1.01			
F_{MSY}	0.26	0.20	0.34			
B_{MSY}	17935.4	14217.0	23129.6			
MSY	4731.9	4279.6	5175.8			
B_{1950}/K	0.97	0.78	1.12			
B_{2017}/K	0.12	0.07	0.20			
$B_{2017}/B_{\mathrm{MSY}}$	0.33	0.18	0.54			
$F_{2017}/F_{\mathrm{MSY}}$	1.99	1.21	3.62			

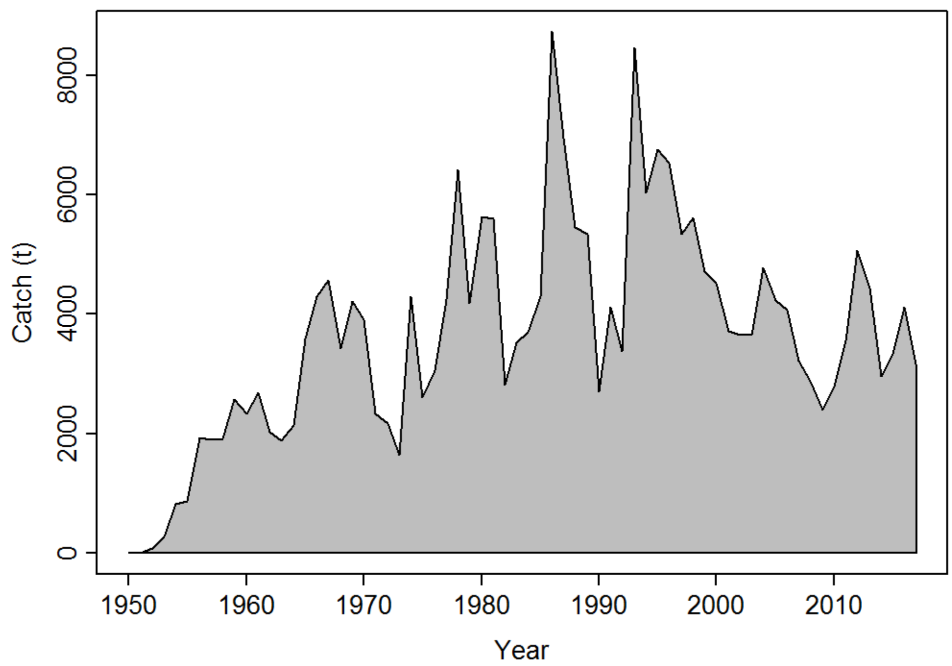

Figure 1. Time-series of estimated catch in metric tons (t) for Indian Ocean striped marlin (1950-2017) used in the Base Case (S5) Scenario.

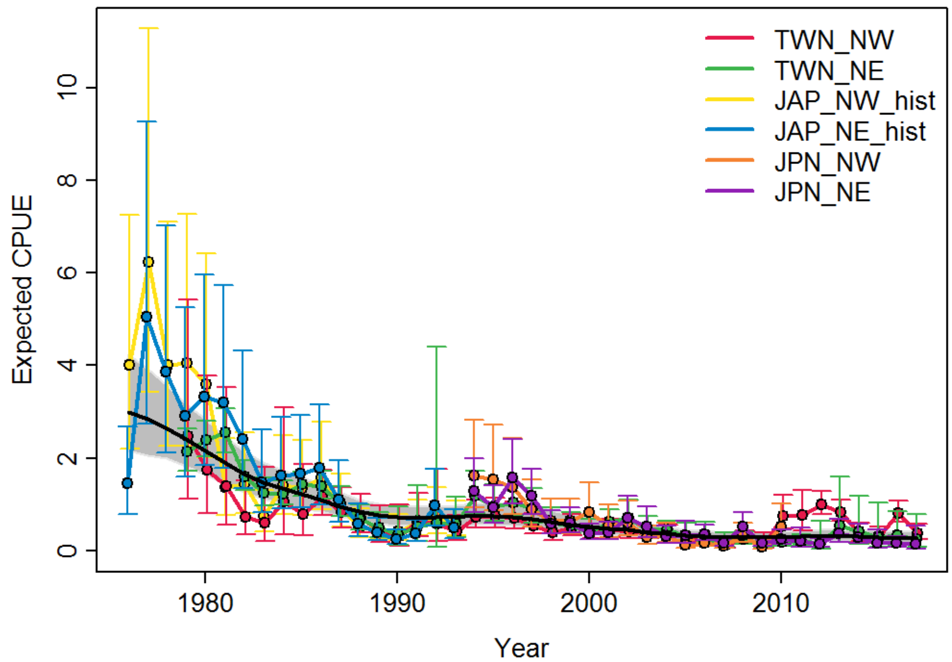

Figure 2. Time-series of six standardized CPUE series for striped marlin in the Indian Ocean. The mean CPUE trend (solid black line) was produced using the state-space CPUE averaging tool implemented in JABBA. The underlying abundance trend is treated as an unobservable state variable that follows a 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.

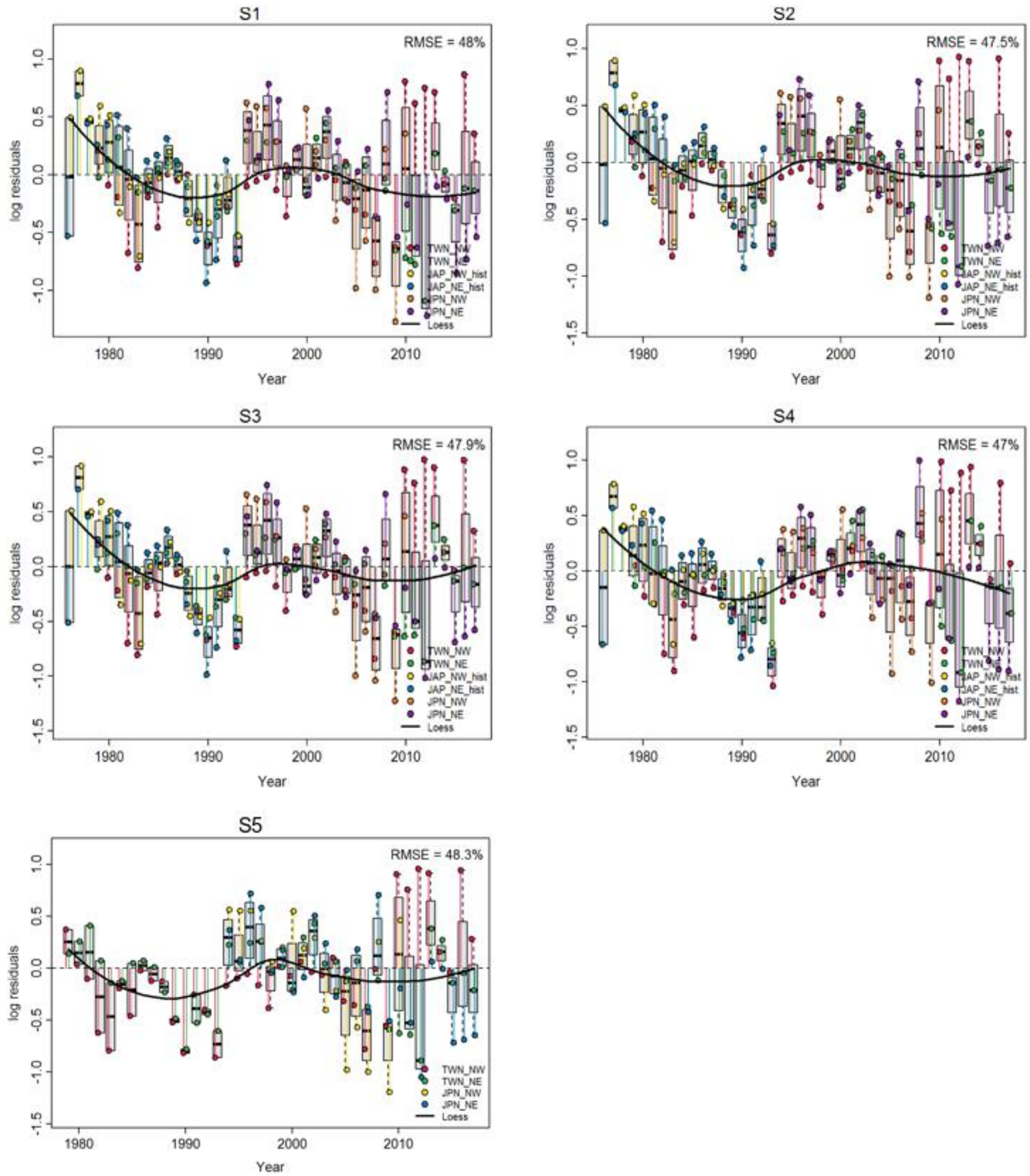

Figure 3. JABBA residual diagnostic plots for Scenarios S1-S5, showing alternative sets of CPUE indices for Indian Ocean striped marlin. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals.

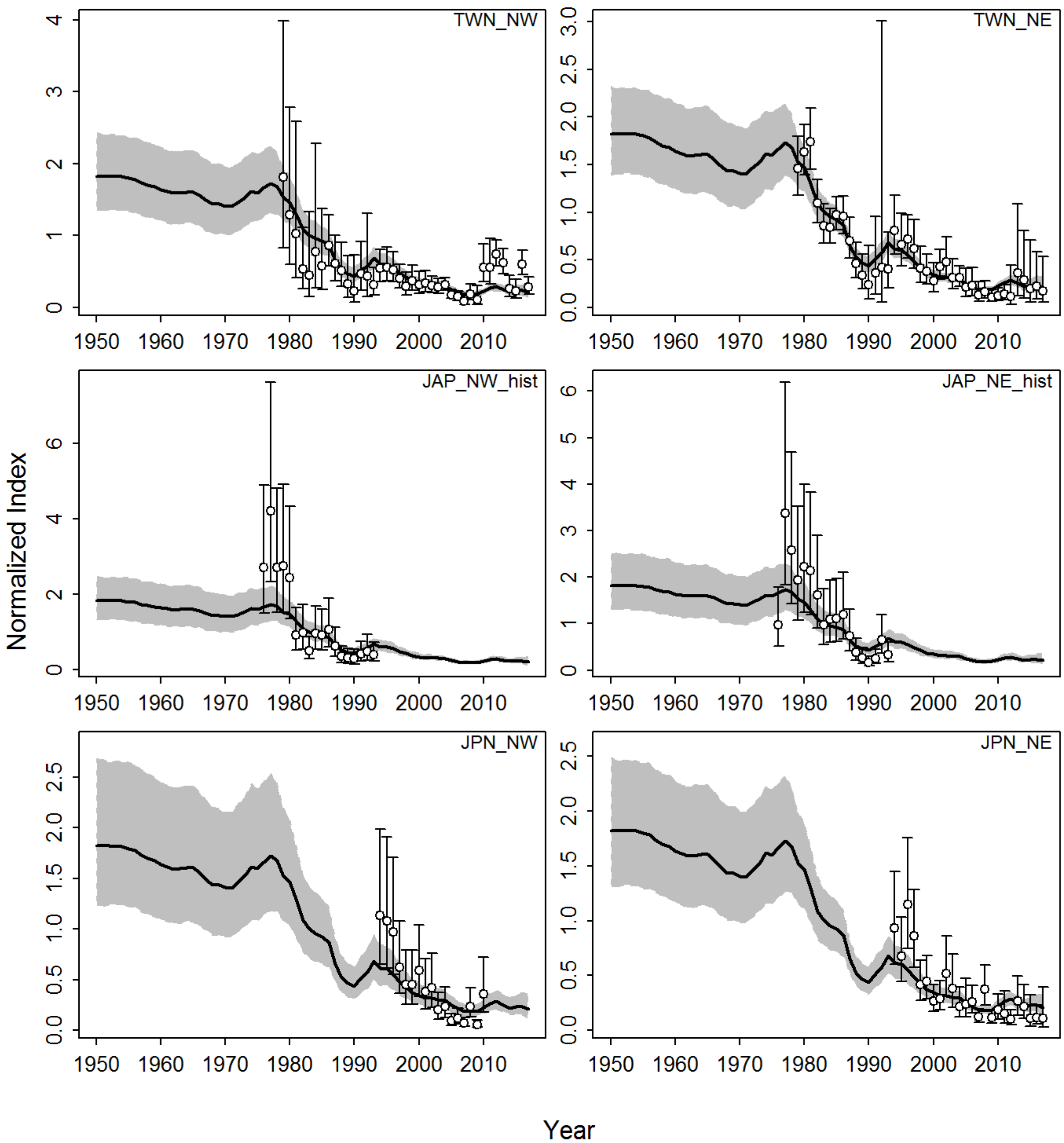

Figure 4. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of striped marlin in the Indian Ocean for the Bayesian state-space surplus production model JABBA. Shaded grey area indicates 95% C.I.

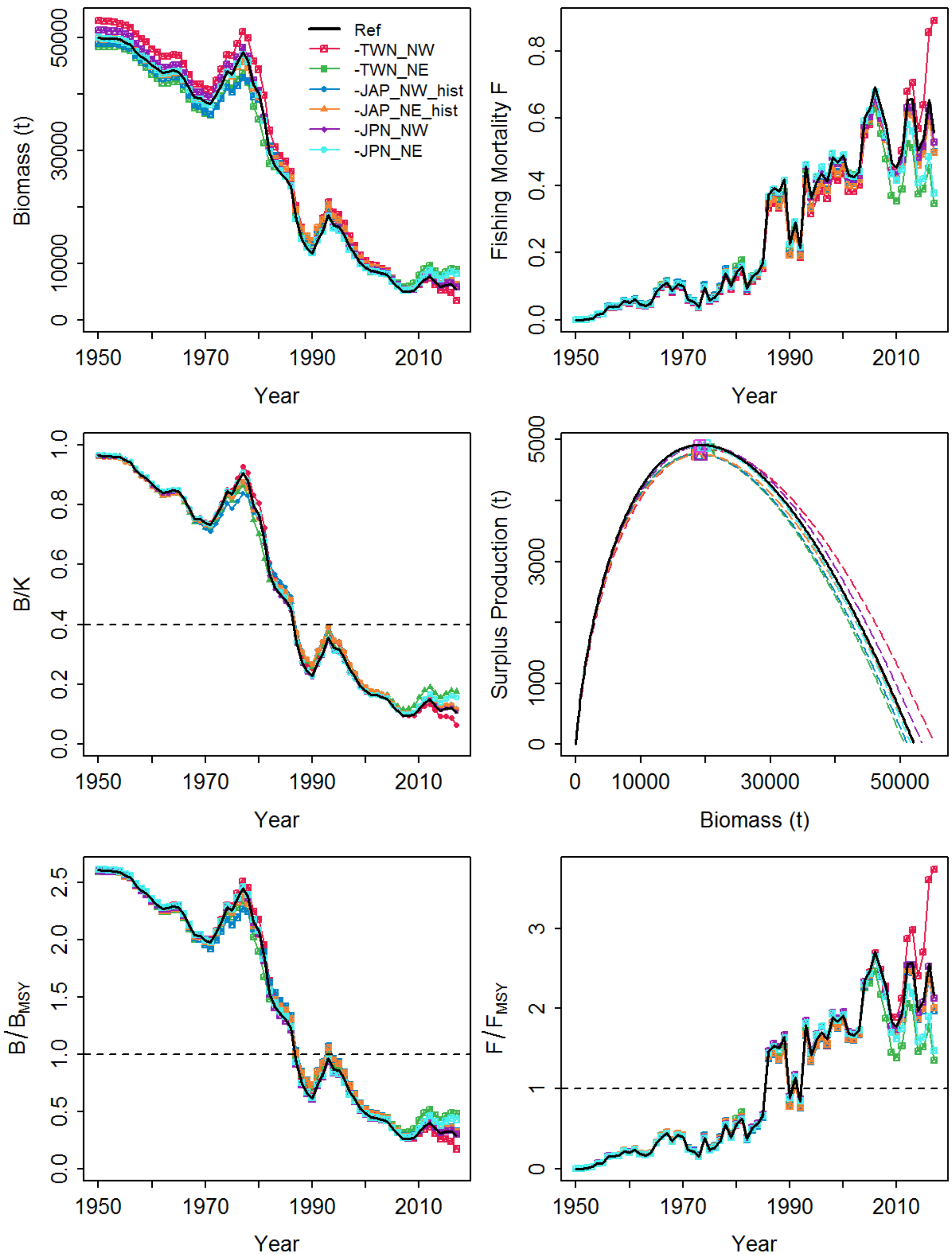

Figure 5. Sensitivity analysis showing the influence of removing one CPUE series at a time on predicted stock biomass (*B*), fishing mortality (*F*), proportion of pristine biomass (*B/K*), surplus production function (maximum = MSY) and the stock status trajectories F/F_{MSY} and B/B_{MSY} for the reference scenario (S2) for Indian Ocean striped marlin.

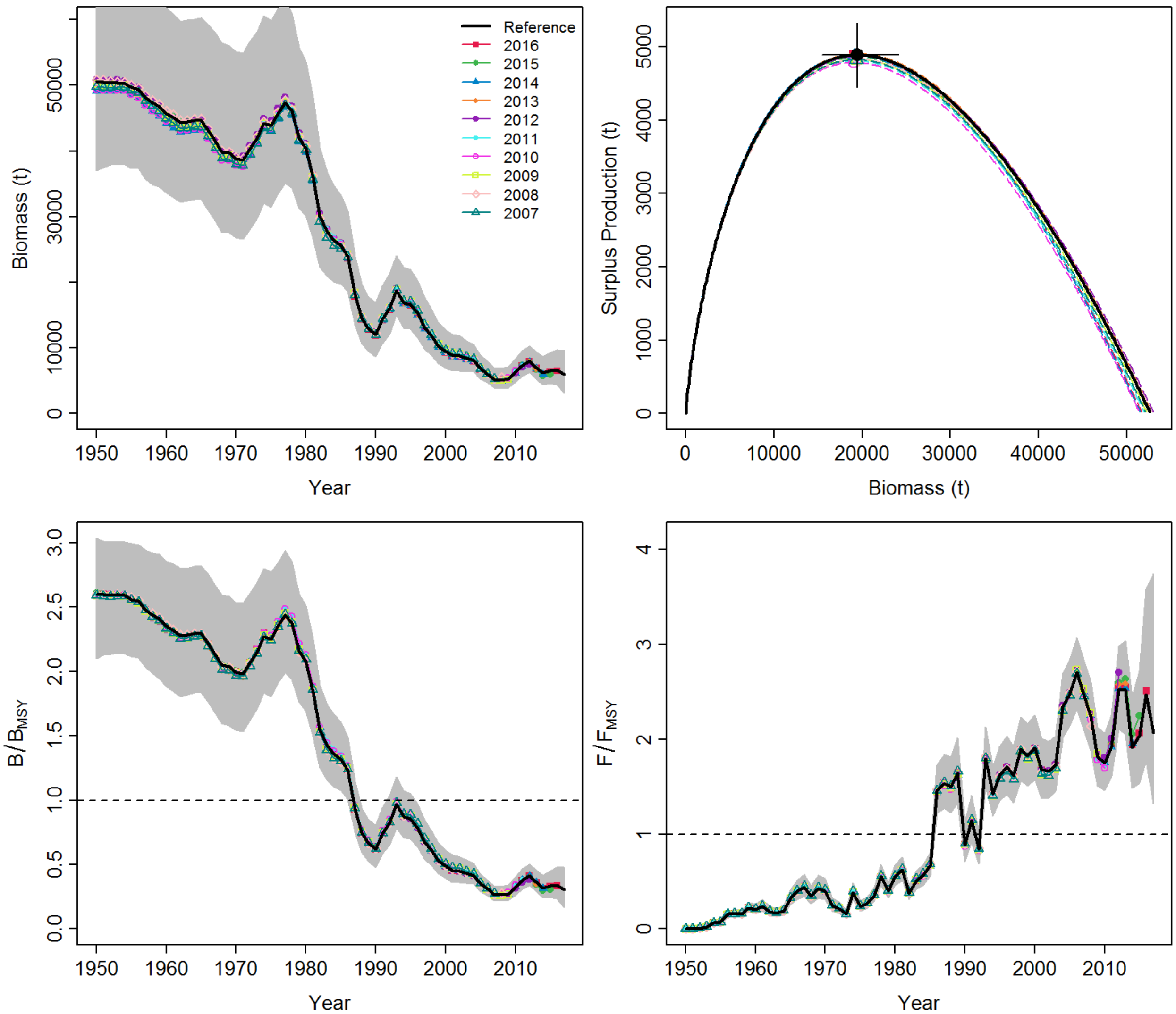

Figure 6. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), *B/B_{MSY}* and *F/F_{MSY}* for the Indian Ocean striped marlin JABBA Reference Scenario (S2). The label "Reference" indicates the reference case model fits and associated 95% CIs to the entire time series 1950-2017. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2007. Grey shaded areas denote the 95% CIs, which are indicated by crosshair for *B_{MSY}* and MSY defining the maximum of the surplus production curve.

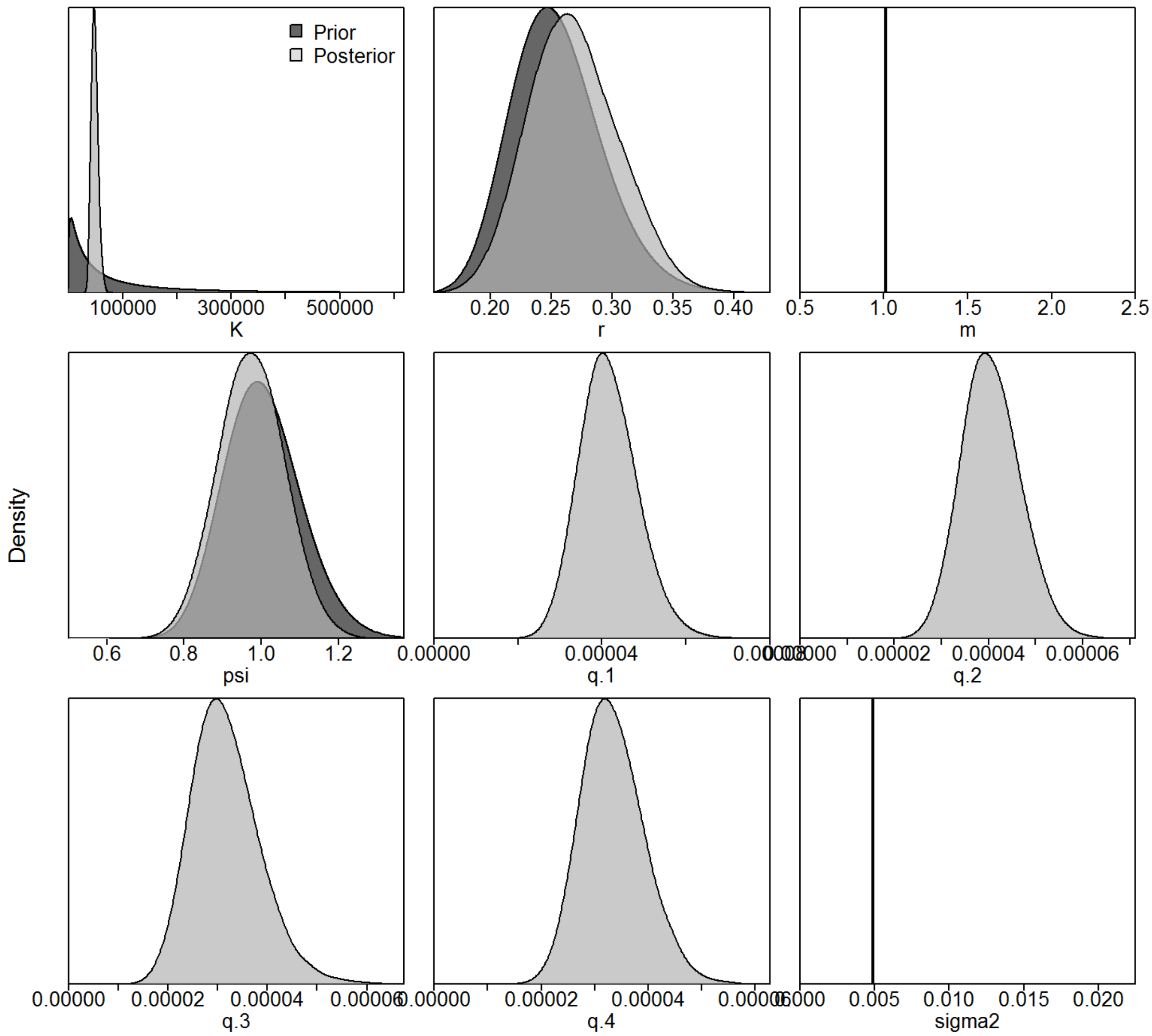

Figure 7. Prior and posterior distribution of various model and management parameters for the Bayesian state-space surplus production model Base Case (S5) for striped marlin in the Indian Ocean.

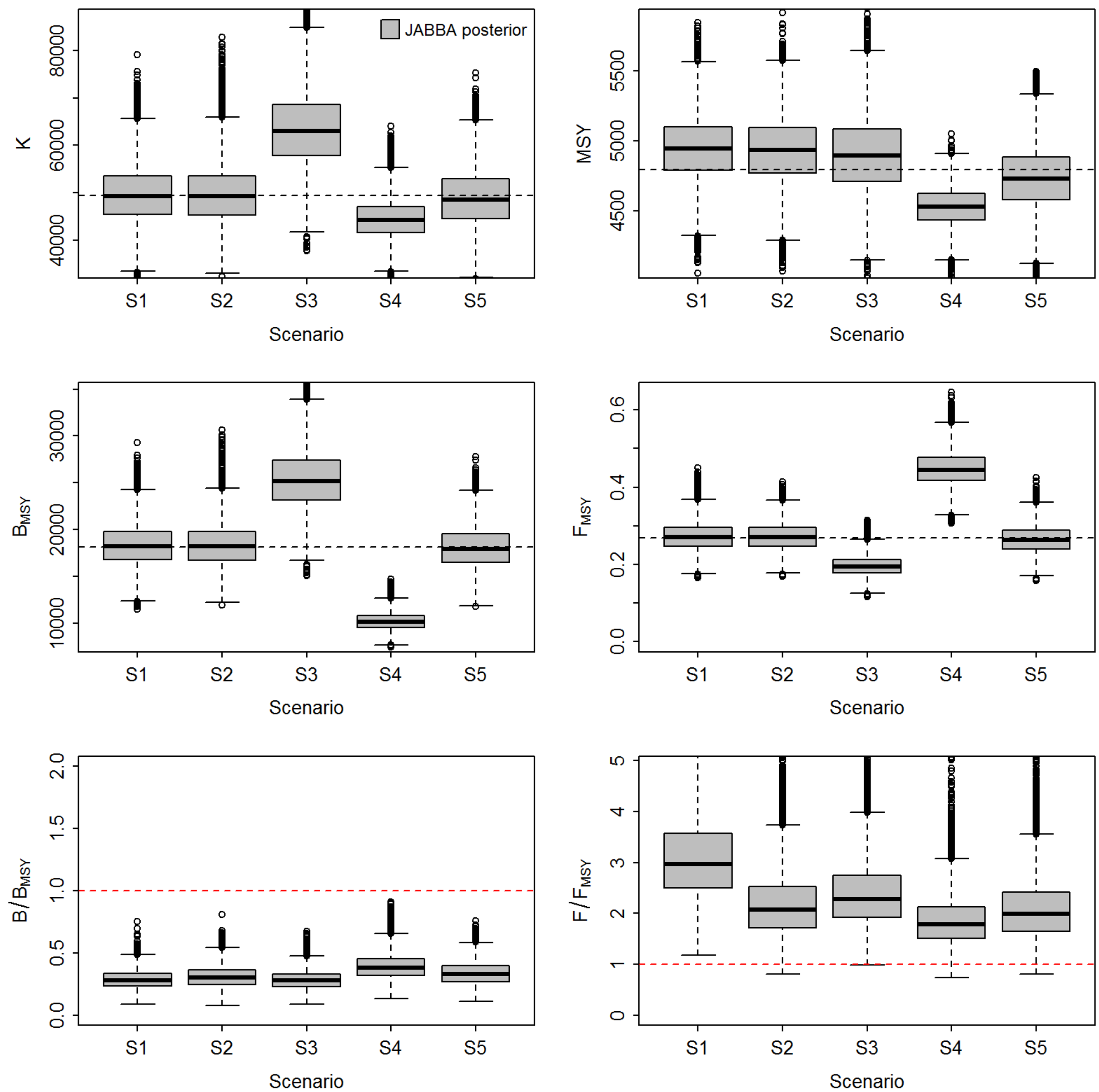

Figure 8. Boxplots summarizing the posterior distributions depicting the stock status for scenarios S1-S5, where B/B_{MSY} and F/F_{MSY} are presented for the final assessment year 2017. Dashed lines denote means across all of the scenarios.

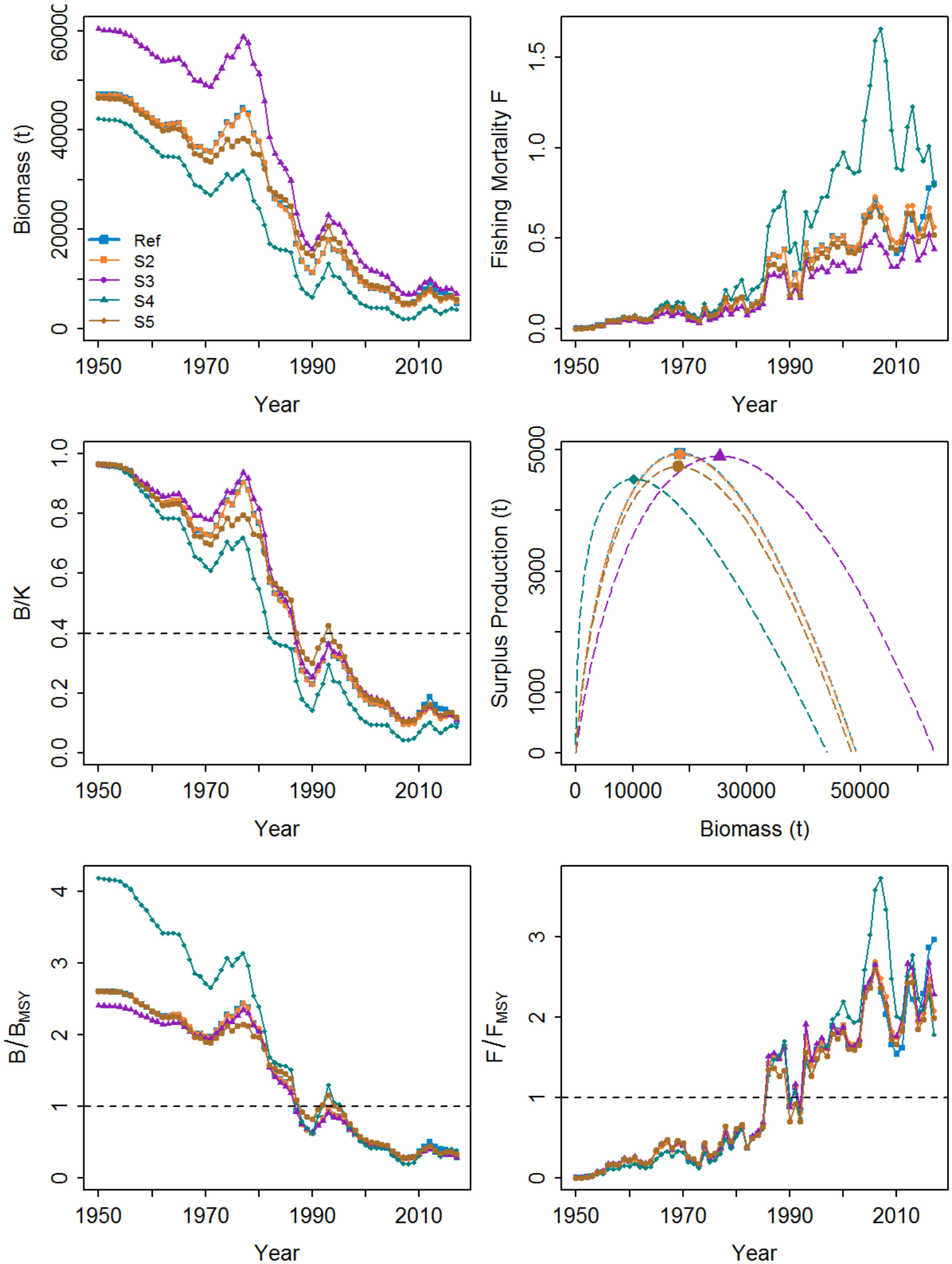

Figure 9. A comparison of stock biomass (t), fishing mortality (*F*), proportion of pristine biomass (*B/K*), surplus production function (maximum = MSY) and the stock status trajectories F/F_{MSY} and B/B_{MSY} between the five scenarios applied to the Indian Ocean striped marlin assessment.

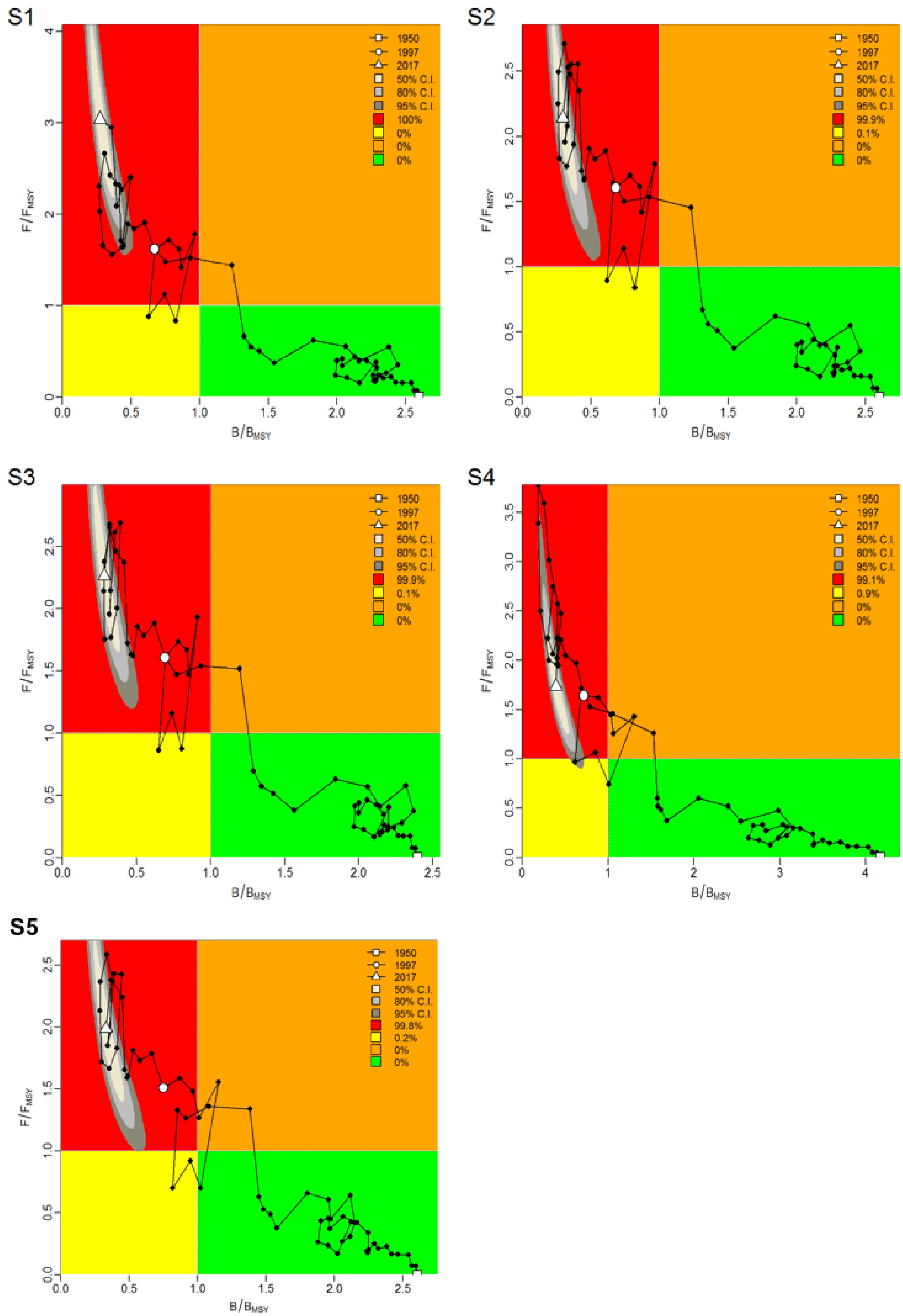

Figure 10. Kobe diagram showing the estimated trajectories (1950-2017) of *B/B_{MSY}* and *F/F_{MSY}* for all five scenarios of the Bayesian state-space surplus production model for the Indian Ocean striped marlin stock.

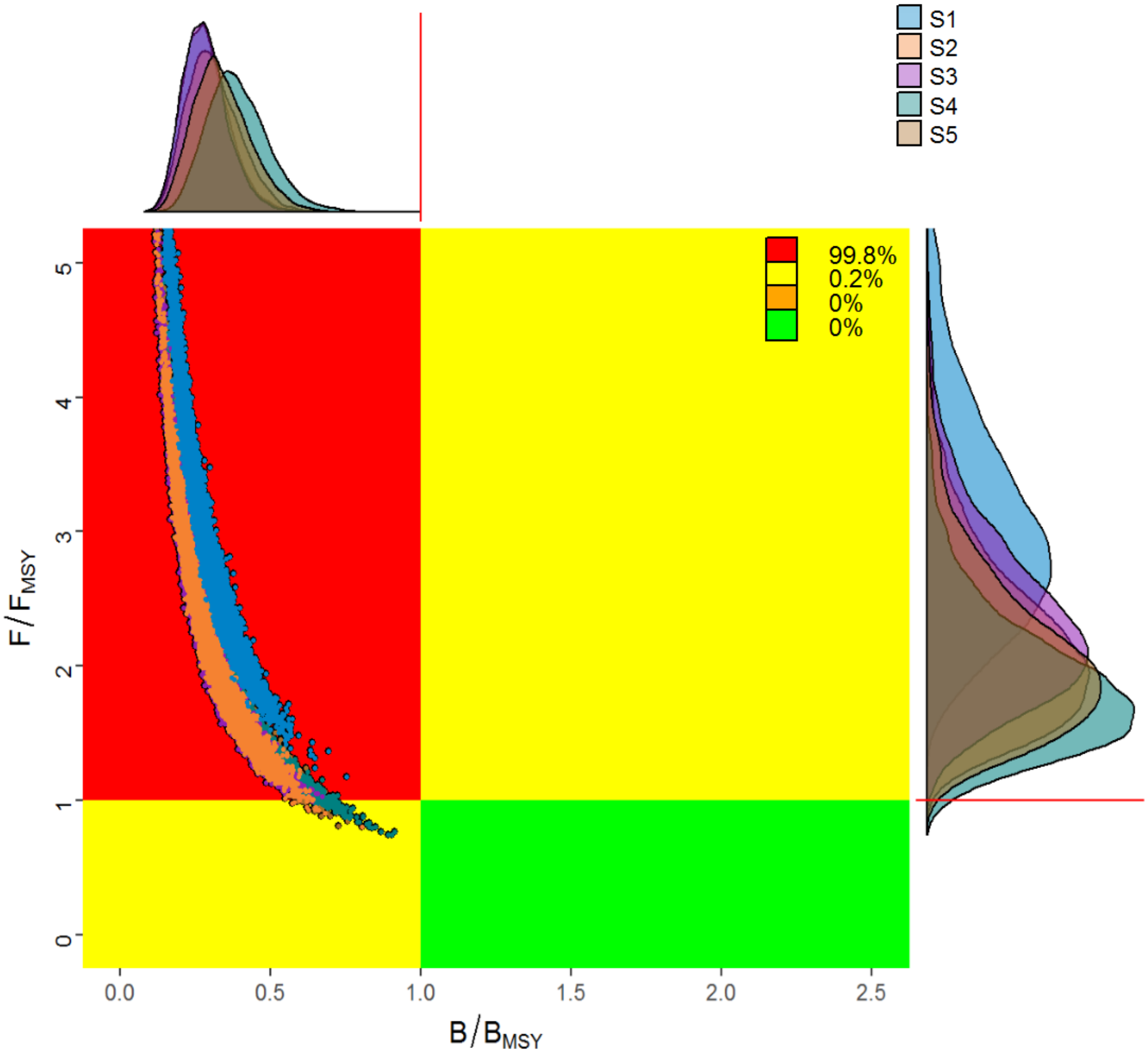

Figure 11. Combined Kobe phase plot for all the scenarios of the Bayesian state-space surplus production model for the Indian Ocean striped marlin stock.

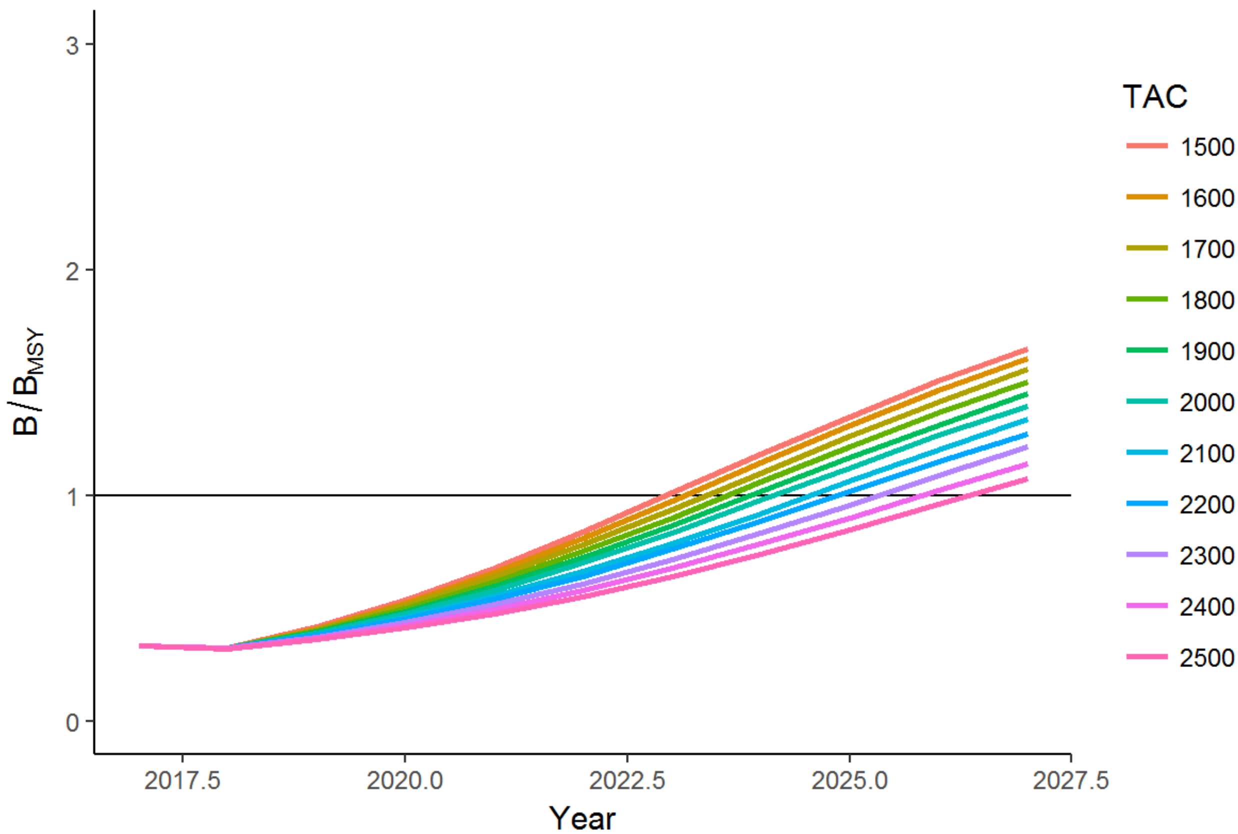

Figure 12. Projections based on the JABBA Base Case scenario (S5) for Indian Ocean striped marlin for various levels of future catch. The range of constant catch (TAC) estimates was determined according to the new IOTC BIL Res (18-05) - *Options to reduce fishing mortality with a view to recover and/or maintain the stocks in the Green zone of the Kobe Plot with levels of probability ranging from 60 to 90% by 2026 at latest*. The dashed line denotes BMSY.