BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL *JABBA* ASSESSMENT OF INDIAN OCEAN BLACK MARLIN (MAKAIRA INDICA) STOCK

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SUMMARY

An initial assessment of the Indian Ocean black marlin (*Makaira indica*) was run using Bayesian State-Space Surplus Production Models in the open-source stock assessment tool JABBA. Four scenarios were selected based on alternative specifications of the Pella-Tomlinson model type that incorporated two differing nominal catch data time-series, three different priors for the intrinsic rate of population increase r and associated input values of B_{MSY}/K, which determine the inflection point of the surplus production curve. Relative abundance (CPUE) fits are generally comparable among all four scenarios in showing a steady decline from 1979 until 2005, after which signals of an increasing trend become apparent. A general increase in black marlin catches is evident from 1990 onward with steep increases from 2010. A 'drop one' sensitivity analysis on CPUE indices indicates that omitting either of the Taiwan,China indices (NE and NW) would influence the management reference point estimates B/B_{MSY} and F/F_{MSY}. The retrospective analysis produced an undesirable retrospective pattern as evident by systematic negative departures from the Reference Case predictions. This pattern becomes particularly strong from 2014 onward when the increase in total catch accelerated. Furthermore, an implausible trajectory is evident in all four Kobe biplots, which suggest that black marlin B/B_{MSY} increases with an associated increase in F/F_{MSY} for the period 2010-2017. These diagnostics highlight the poor performance with regard to the robustness of estimates and forward projections of B/B_{MSY} and F/F_{MSY} in this assessment and suggest model misspecification due to a simultaneous increase of both catch and CPUE, which is in conflict with the basic population dynamics principles. As such, resultant management reference points should be treated with caution and not be used to inform management decisions. It is recommended that further scrutiny be applied to black marlin catch and effort data for the Indian Ocean.

KEY WORDS

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

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1. Introduction

In 2014, a Stock Reduction Analysis based only on catch data was used to assess the status of Indian Ocean black marlin, which was then classified as "subject to overfishing". At the WPB14 in 2016, the Indian Ocean Commission (IOTC) carried out an assessment for black marlin (*Makaira indica*) using two different model types; the Surplus Production Model ASPIC and a Bayesian State Space Production Model (BSPM). The assessments comprised catch and effort data through 2015 and estimations of management reference points (IOTC, 2017). Results of both models included in the 2016 assessment were similar. The ASPIC results indicated that the black marlin stock was overfished and currently subjected to overfishing (F/F_{MSY} = 2.02 and B/B_{MSY} = 0.59). Risk assessments derived from ASPIC suggested that even if catch were reduced by 40% of the current catch level there was still a high risk (>70%) that F/F_{MSY} would remain above 1 (Yokoi and Nishida, 2016). Results from the BSPM model indicated that the black marlin stock had been overfished during the last 10-15 years (Andrade, 2016).

Here we provide an updated assessment of the Indian Ocean black 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) and 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 four alternative scenarios are discussed in terms of robustness and inference of 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 black marlin at the WPB16. Two differing nominal catch scenarios were proposed: *IOTC-2018-WPB16-DATA11a* and *IOTC-2018-WPB16-DATA11b*. Both of these catch time-series spanned from 1950 to 2017, with the former providing a continuity run from the 2016 black 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 three fishing fleets: Japan, Taiwan,China and Indonesia (Table 1). For this assessment, the Taiwan,China CPUE index was spatially limited to the northern Indian Ocean, and further disaggregated into the North-East and North-West regions. This resulted in a total of four 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 black marlin, we considered four alternative specifications of the Pella-Tomlinson model type based on two differing nominal catch data time-series, three differing *r* priors and associated input values of B_{MSY}/K. The input priors were objectively derived from the simulations in an Age Structured Equilibrium Model ASEM (Winker *et al*., 2018b; Winker *et al*., 2018c), which allowed approximating the parameterizations based on range of stock recruitment steepness values for the stock recruitment relationship (h = 0.4, h = 0.5 and h = 0.6), 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 both of the 2016 assessments (Winker *et al*., 2018c). In addition, we ran a scenario with a higher *r* prior that corresponds to a higher steepness value of h = 0.6 and a scenario with a lower *r* prior based on h = 0.4 (Table 2). This resulted in the formulation of the following four scenario specifications:

- **S1 (Cont.):** for B_{MSY}/K = 0.37 (h = 0.5), *r* prior *LN* ~ (log (0.19), 0.30)), catch data = Data 11a, including all CPUE time-series.

- **S2 (Ref.):** for B_{MSY}/K = 0.37 (h = 0.5), *r* prior *LN* ~ (log (0.19), 0.30)), catch data = Data 11b, including all CPUE time-series.

- **S3:** for B_{MSY}/K = 0.41 (h = 0.4), *r* prior *LN* ~ (log (0.16), 0.30)), catch data = Data 11b, including all CPUE time-series.

- **S4:** for B_{MSY}/K = 0.34 (h = 0.6), *r* prior *LN* ~ (log (0.21), 0.30)), catch data = Data 11b, including all CPUE time-series.

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, 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 black marlin in the Indian Ocean were relatively low prior to 1990, and only exceeded 2,500 tons for the first time in 1992 (Figure 1). Thereafter, catches increased significantly to a similar maximum of 22,445 tons (Data 11a) or 21,070 tons (Data11b) in 2017, depending on which catch estimate time-series is applied. In contrast to the catch series revision for striped marlin, there appears to no clearly discernible difference in catch estimates between Data 11a and Data 11b. Relative abundance (CPUE) estimates steadily decline from 1979 until 2005, after which signals for a general positive (increasing) trend become evident. CPUE model fits were generally comparable among all four scenarios (Figures 2 and 3), which was also supported by the similarity in the goodness-of-fits as judged by the narrow range RMSE values (RMSE = 25.9-26.1%). The Taiwan,China CPUE trends (NW and NW) showed a good fit to the observed data, with the exception of the last five years for the Taiwan,China NE index (Figure 4). The model also appears to describe both the Japanese and Indonesian observed CPUE data adequately, noting that the latter is limited to the period when there is a positive CPUE trend (2005-2017).

The 'drop one' sensitivity analysis indicates that omitting either of the Taiwan,China indices would influence the management reference point estimates B/B_{MSY} and F/F_{MSY} . Excluding the

TWN NE index would provide a more optimistic result while omitting the TWN NW index would result in a more pessimistic assessment outcome (Figure 5). Notably, excluding the Taiwan,China NW would result in an estimate of F/F_{MSY} greater than 1. In contrast, omitting either the Japanese or Indonesian CPUE time-series would have a negligible effect on the assessment management reference points.

The retrospective analysis produced highly variable stock status estimates with strong evidence of an undesirable retrospective pattern (Figure 6). Departures from the Reference Case predictions are notable, particularly from 2014 onward, all of which result in a more pessimistic outlook of the stock status than the Reference Case. Of particular concern is the plasticity of the surplus production function and the subsequent estimates of *MSY* and *K*. The estimate of *K* for the Reference Case (2017) is almost double that estimated when only CPUE data up to 2013 is fitted. These diagnostics highlight the poor performance with regards to the robustness of estimates and forward projections of B/B_{MSY} and F/F_{MSY} in this assessment.

All scenarios produce B/B_{MSY} trajectories that steadily declined from the late 1980s to when it levelled in 2005 (Figure 9). Thereafter, B/B_{MSY} increased from 2008 to 2017. In contrast, F/F_{MSY} increased steadily from 1990 to 2017 with a brief period of stability between 2004 and 2010. The MSY estimates showed little variation, ranging between 11,807 and 13,493 tons for all four scenarios (Table 3) and the corresponding range of B_{MSY} estimates was between 58,455 tons (S4) and 85,716 tons (S3). The median F/F_{MSY} estimates ranged between 0.87 (S4) and 1.19 (S3) and the Reference Case F_{MSY} estimate was 0.97. The range of median estimates for B/B_{MSY} was 1.50 - 1.79 and the range for *B/K* median estimates was 0.61 - 0.62 (Table 3).

Individual Kobe biplots were similar among all scenarios and each indicated that the biomass remains above B_{MSY} despite two of the four scenarios indicating that overfishing ($F/F_{MSY}>1$) may be occurring (Figure 10). Notably, an implausible trajectory is evident in all four Kobe biplots which suggest that black marlin B/B_{MSY} increases with an associated increase in F/F_{MSY} for the period 2010-2017.

The results of this initial JABBA assessment suggest severe model misspecification which is likely a result of poor quality input data (catch and CPUE). The observed increasing CPUE trend in conjunction with a significant increase in catch since ~2010 pushes the limits of biological plausibility. As a result, the surplus production function exhibits a strong, systematic retrospective pattern, which arises from compensating for simultaneous increases in catch and relative abundance by inflating the pristine biomass estimate (*K*). The observed systematic deviations in the retrospective analysis results provide little confidence in the predictive capabilities of the assessment and, consequently, the assessment's estimated fishery management reference points should not be used to inform management decisions. It is recommended that further scrutiny be applied to black marlin catch and effort data for the Indian Ocean.

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 black 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 Indian Ocean	1994-2017	JPN
Indonesia Indian Ocean	2005-2017	IND

Table 2. Summary of prior and input parameter assumptions used in the 2018 *JABBA* Indian Ocean black 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 = 0.6 (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	0.19	30%	S1, S2
r (low *h*)		lognormal	0.16	30%	S3
r (high *h*)		lognormal	0.21	30%	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
B_{MSY}/K (low *h*)		fixed	0.41	-	S3
B_{MSY}/K (high *h*)		fixed	0.34	-	S4

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

	Scenario 1 (Cont.)			Scenario 2 (Ref.)		
Estimates	**Median**	**2.50%**	**97.50%**	**Median**	**2.50%**	**97.50%**
K	190724	126258	330939	196337	123004	322837
r	0.18	0.11	0.29	0.18	0.11	0.30
ψ (*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}	0.18	0.11	0.28	0.18	0.11	0.30
B_{MSY}	70582	46725	122472	72660	45521	119474
MSY	12733	9252	18733	12937	9443	18204
B_{1950}/K	0.95	0.77	1.12	0.96	0.77	1.12
B_{2017}/K	0.61	0.47	0.77	0.62	0.49	0.78
$B_{2017}/B_{\mathrm{MSY}}$	1.64	1.27	2.08	1.68	1.32	2.10
$F_{2017}/F_{\mathrm{MSY}}$	1.08	0.62	1.75	0.97	0.60	1.53

	Scenario 3			Scenario 4		
Estimates	**Median**	**2.50%**	**97.50%**	**Median**	**2.50%**	**97.50%**
K	209036	133208	355757	171878	115765	313413
r	0.17	0.10	0.28	0.20	0.12	0.31
ψ (*psi*)	0.97	0.80	1.14	0.97	0.81	1.14
σ_{proc}	0.07	0.07	0.07	0.07	0.07	0.07
m	1.25	1.25	1.25	0.86	0.86	0.86
F_{MSY}	0.14	0.08	0.22	0.23	0.14	0.36
B_{MSY}	85716	54623	145880	58455	39371	106590
MSY	11807	8413	17063	13493	10074	19405
B_{1950}/K	0.95	0.76	1.12	0.96	0.77	1.12
B_{2017}/K	0.62	0.48	0.78	0.61	0.48	0.77
$B_{2017}/B_{\mathrm{MSY}}$	1.50	1.17	1.90	1.79	1.42	2.25
$F_{2017}/F_{\mathrm{MSY}}$	1.19	0.71	1.92	0.87	0.52	1.35

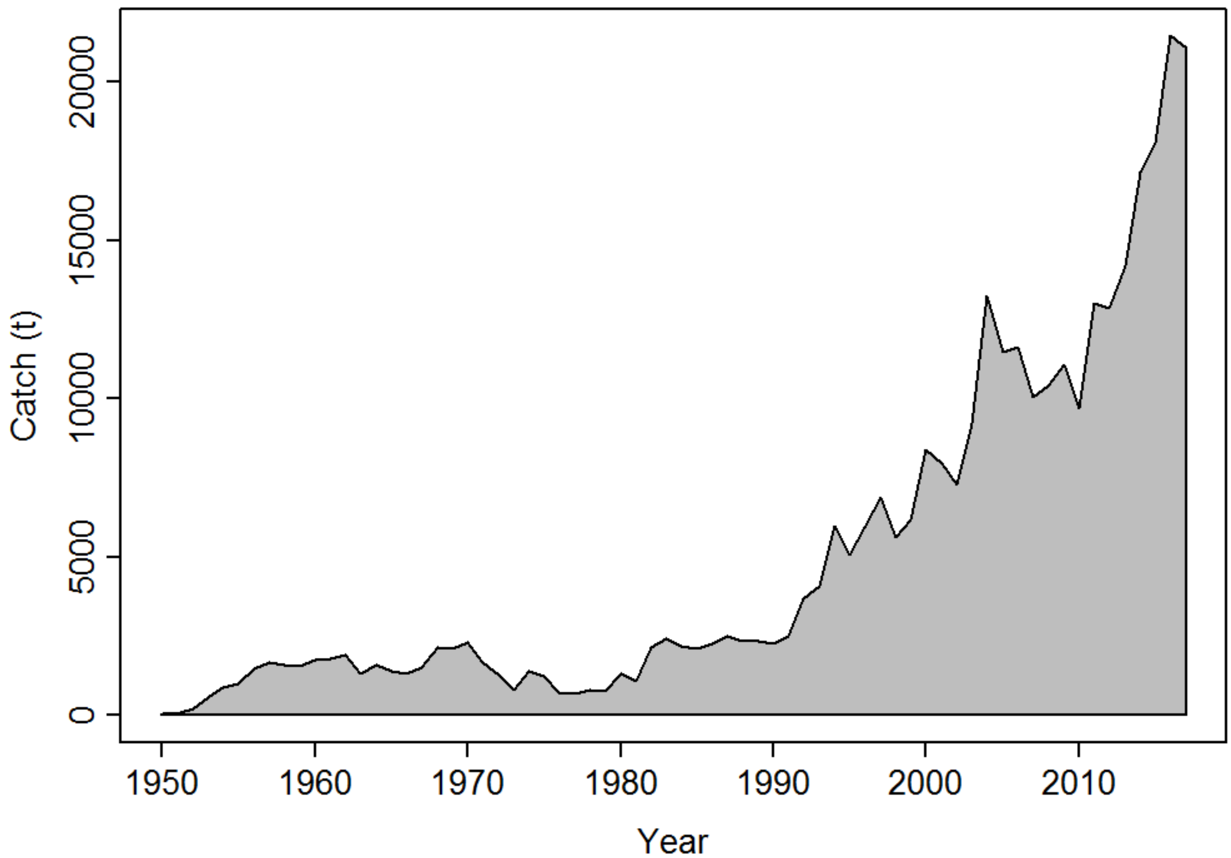

Figure 1. Time-series of estimated catch in metric tons (t) for Indian Ocean black marlin (1950-2017) used in the Reference Case (S2) Scenario.

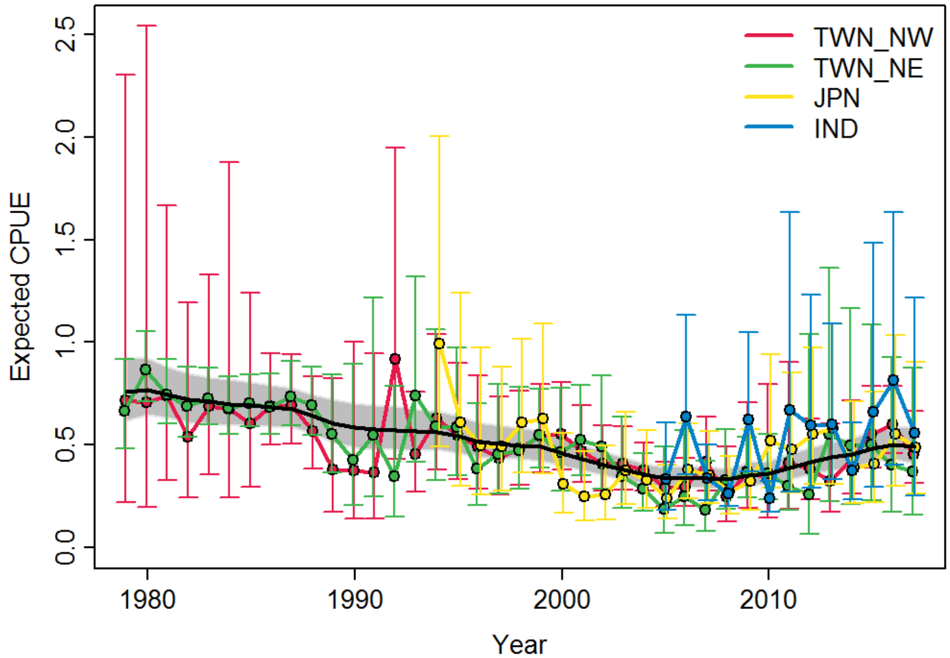

Figure 2. Time-series of four standardized CPUE series for black marlin in the Indian Ocean used in all assessment scenarios. The mean CPUE trend (solid black line) was produced using the state-space CPUE averaging tool implemented in JABBA. The underlying abundance trend is treated as an unobservable 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.

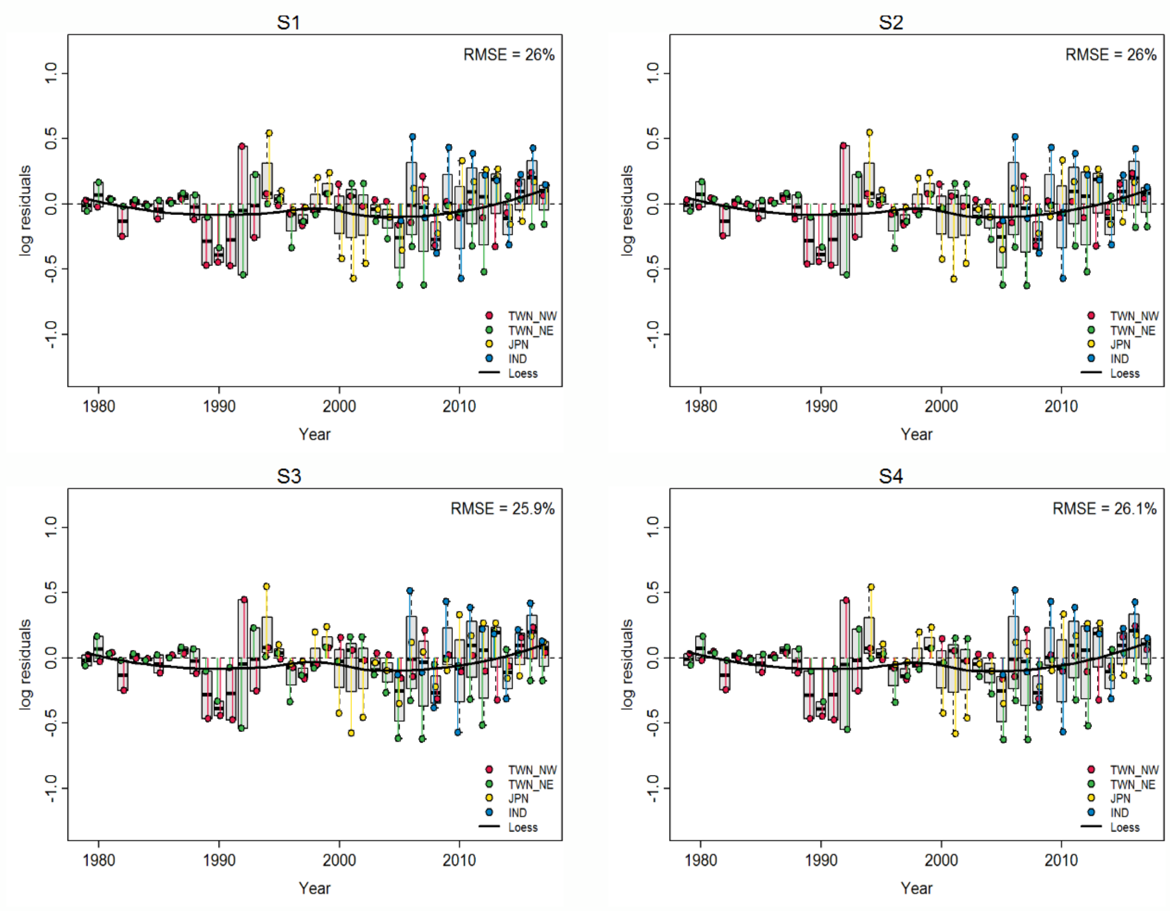

Figure 3. JABBA residual diagnostic plots for Scenarios S1-S4, showing alternative sets of CPUE indices for Indian Ocean black marlin. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals.

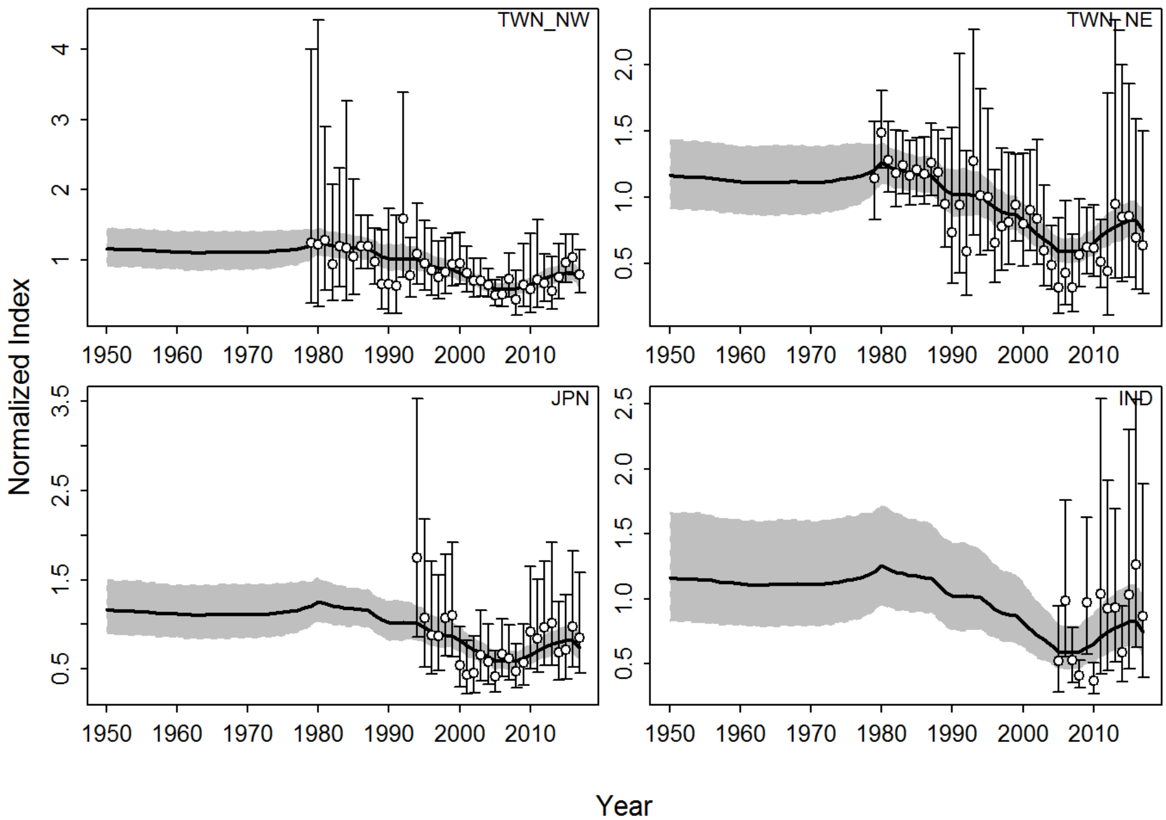

Figure 4. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of black marlin in the Indian Ocean for the Bayesian state-space surplus production model JABBA for all scenarios. Shaded grey area indicates 95% C.I.

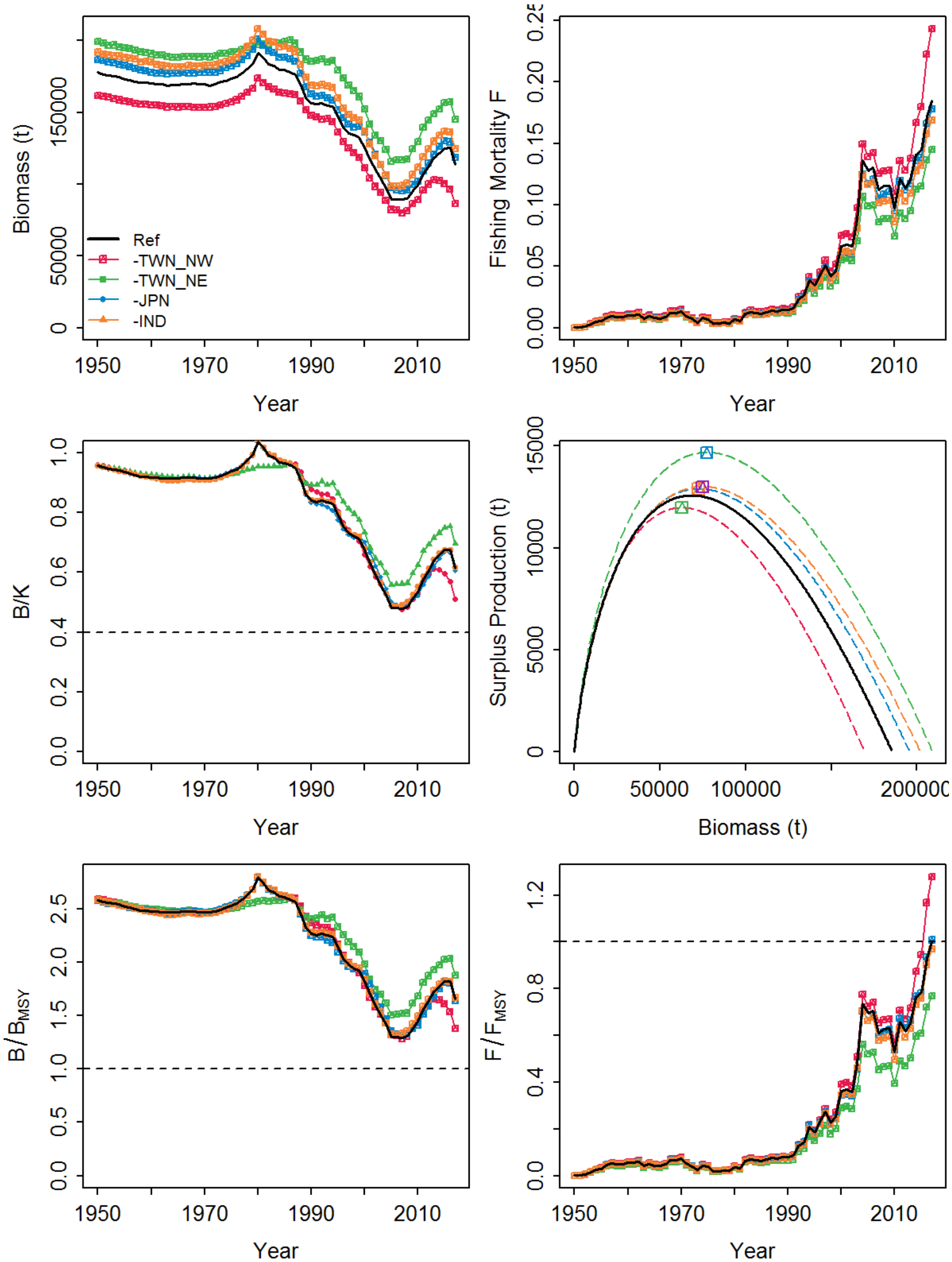

Figure 5. Sensitivity analysis showing the influence of removing one CPUE series at a time on predicted stock biomass (*B*), fishing mortality (*F*), proportion of pristine biomass (*B/K*), surplus production function (maximum = MSY) and the stock status trajectories F/F_{MSY} and B/B_{MSY} for the reference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

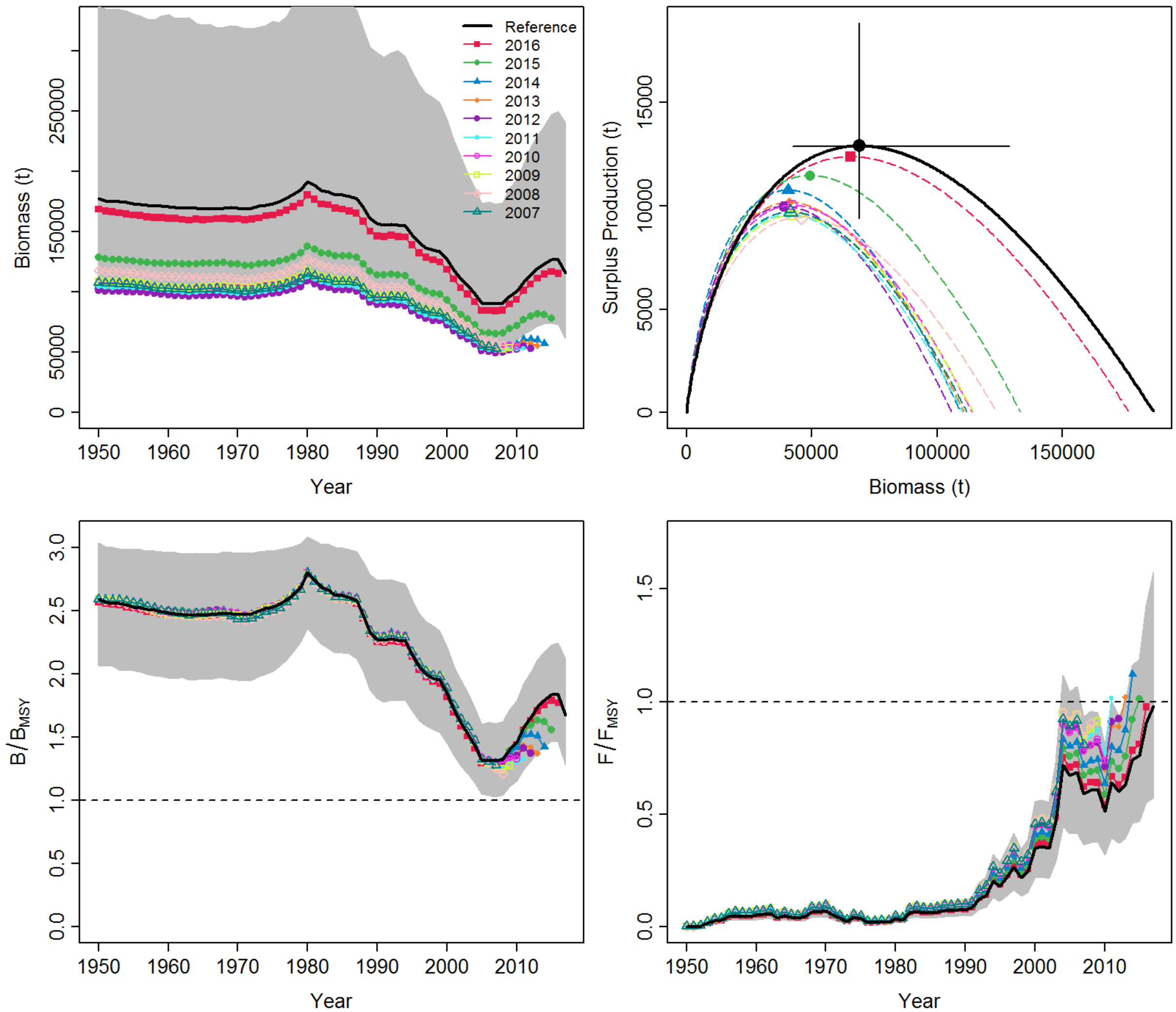

Figure 6. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Indian Ocean black marlin JABBA Reference Scenario (S2). The label "Reference" indicates the reference case model fits and associated 95% CIs to the entire time series 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.

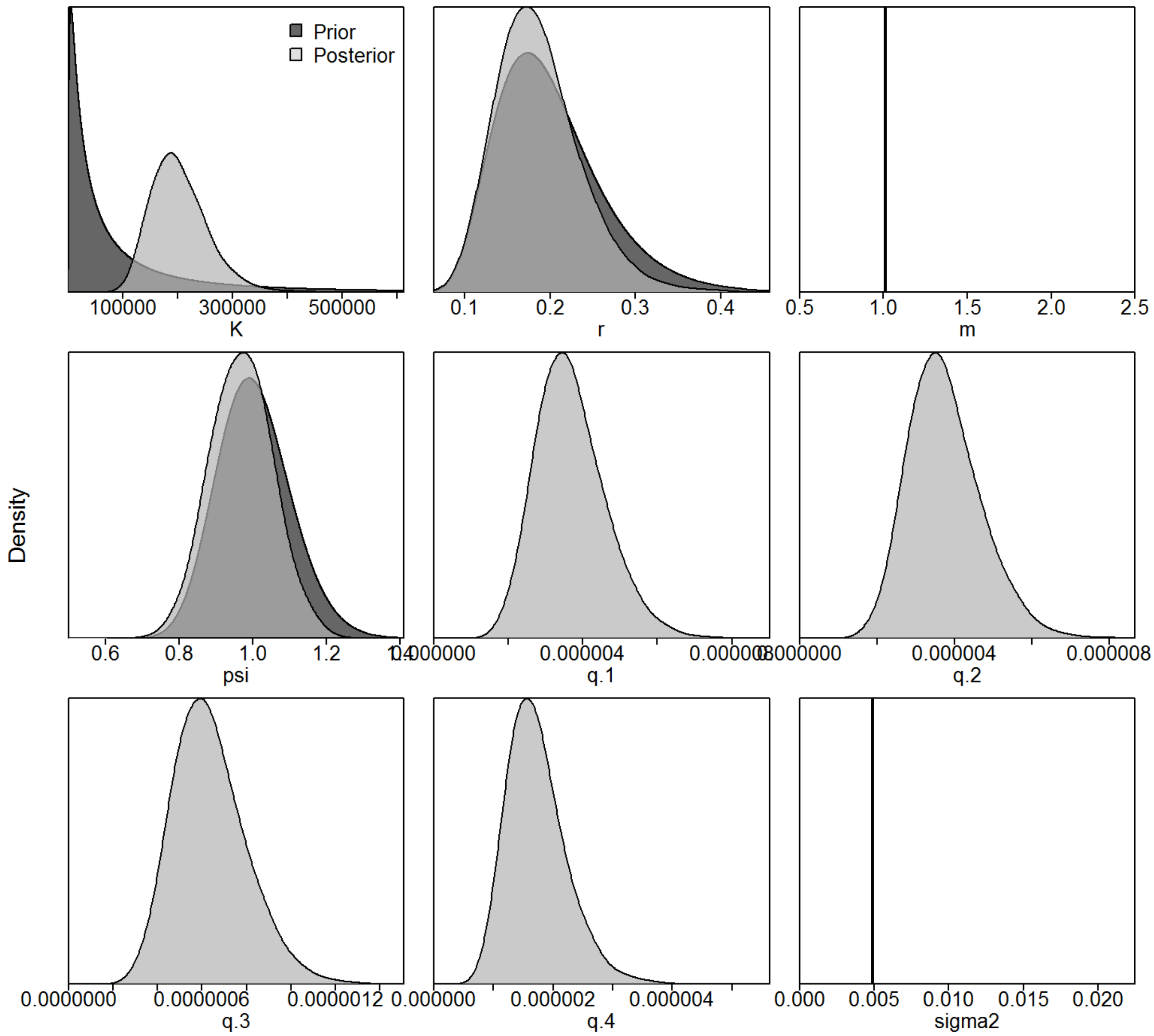

Figure 7. Prior and posterior distribution of various model and management parameters for the Bayesian state-space surplus production model Reference Case (S2) for black marlin in the Indian Ocean.

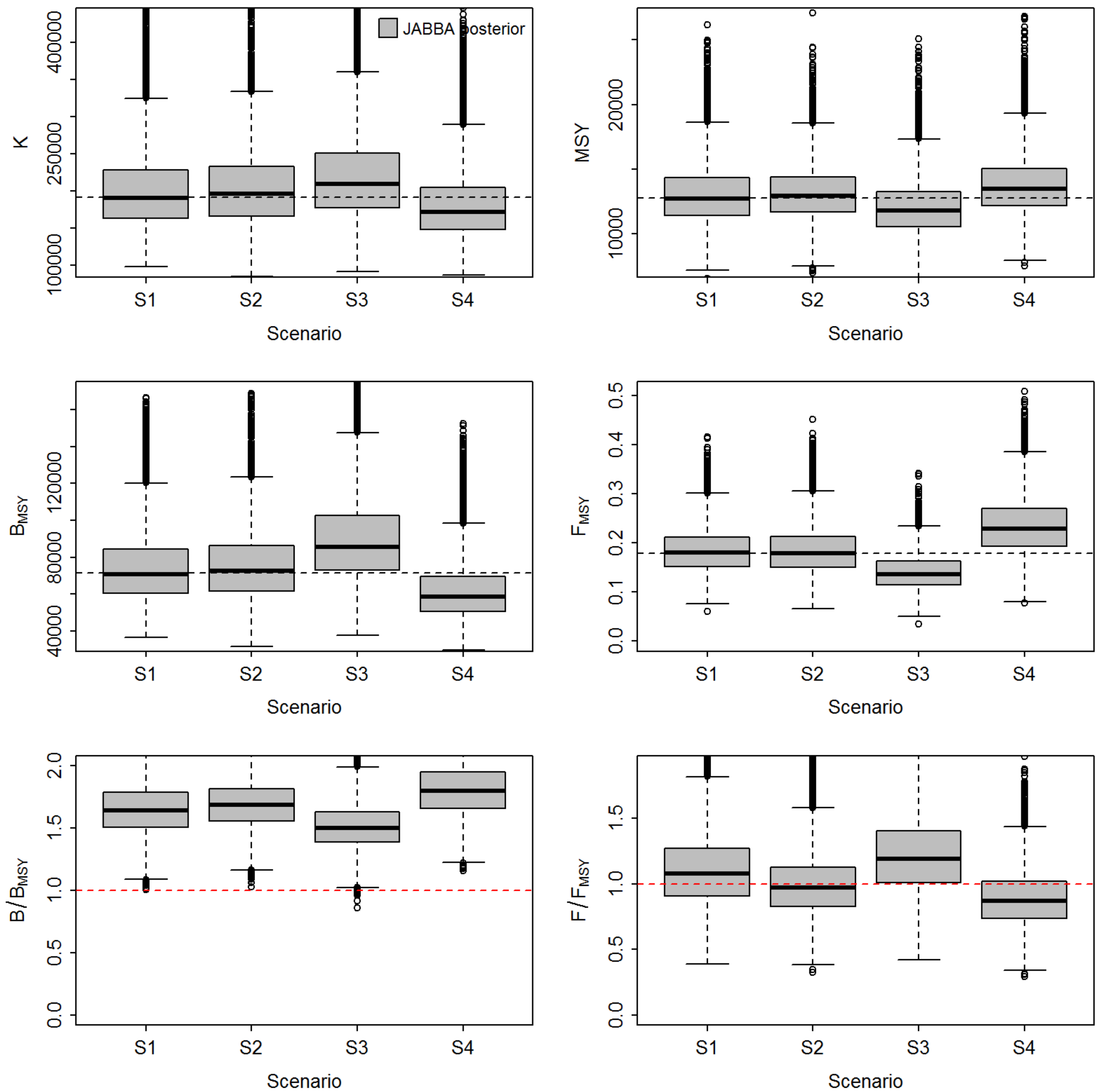

Figure 8. Boxplots summarizing the posterior distributions depicting the stock status for scenarios S1-S4, where B/B_{MSY} and F/F_{MSY} are presented for the final assessment year 2017. Dashed lines denote means across all of the scenarios.

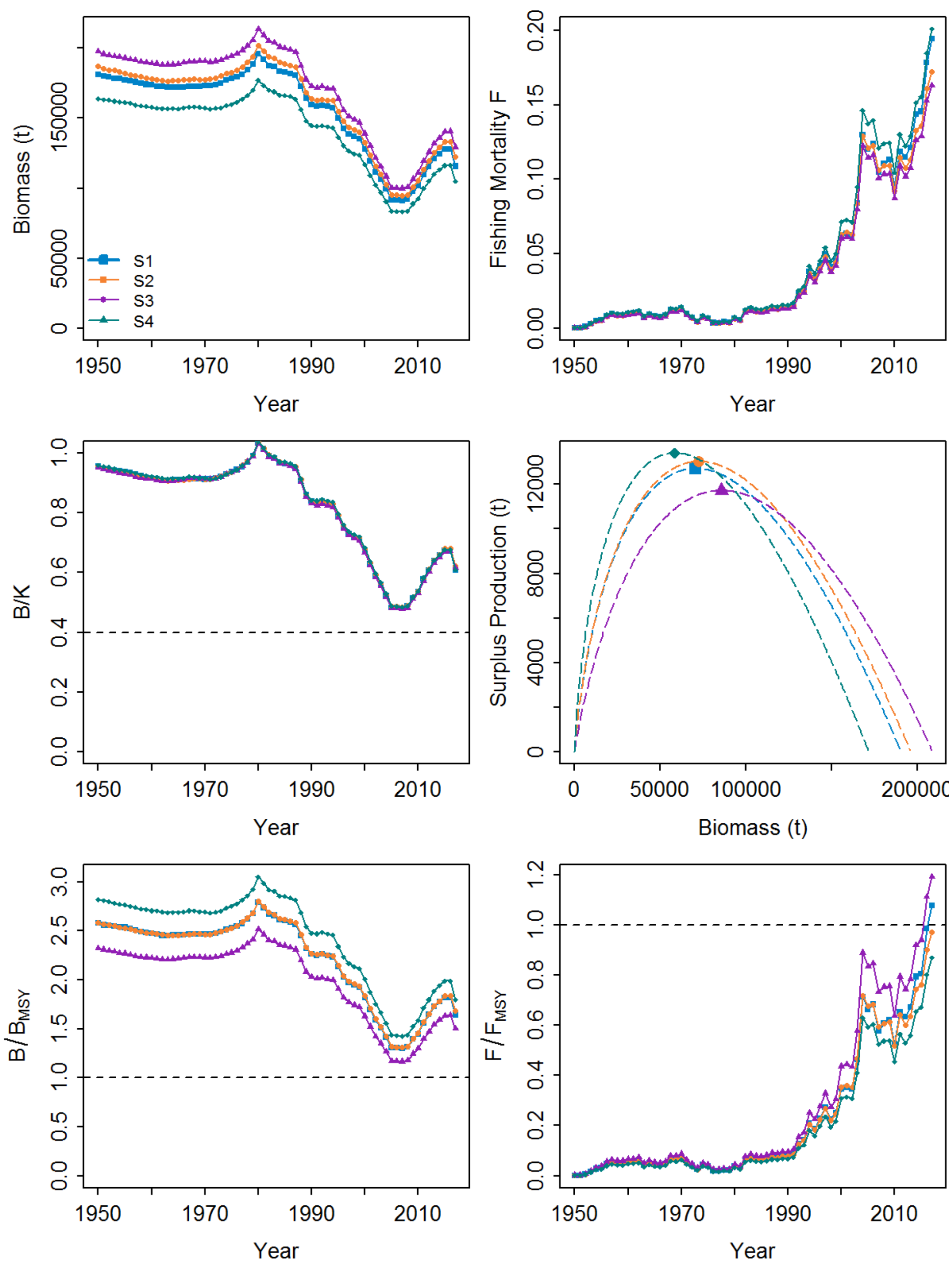

Figure 9. A comparison of stock biomass (t), fishing mortality (*F*), proportion of pristine biomass (*B/K*), surplus production function (maximum = MSY) and the stock status trajectories F/F_{MSY} and B/B_{MSY} between the four scenarios applied to the Indian Ocean black marlin assessment.

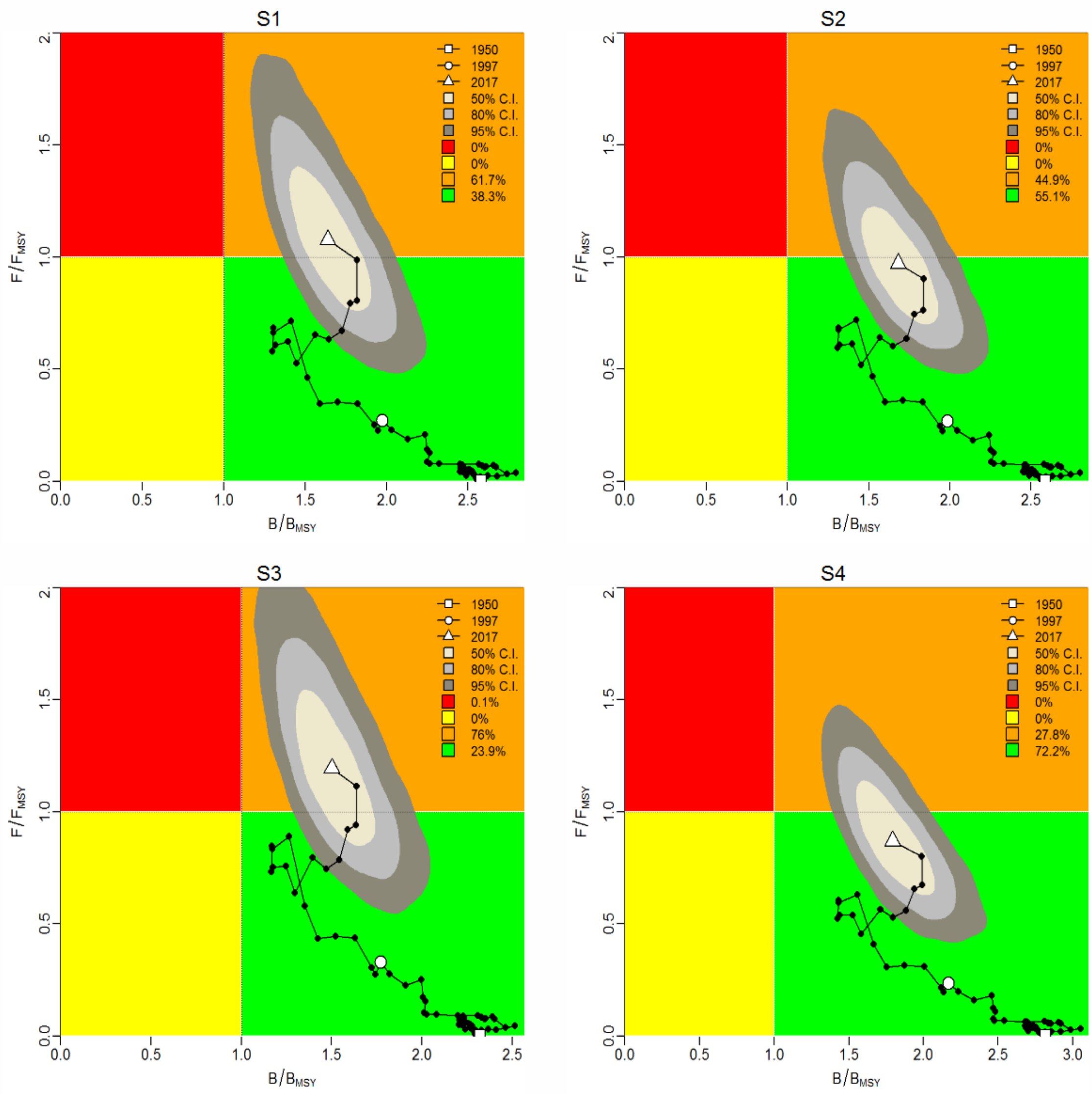

Figure 10. Kobe diagram showing the estimated trajectories (1950-2017) of B/B_{MSY} and F/F_{MSY} for all scenarios of the Bayesian state-space surplus production model for the Indian Ocean black marlin stock.

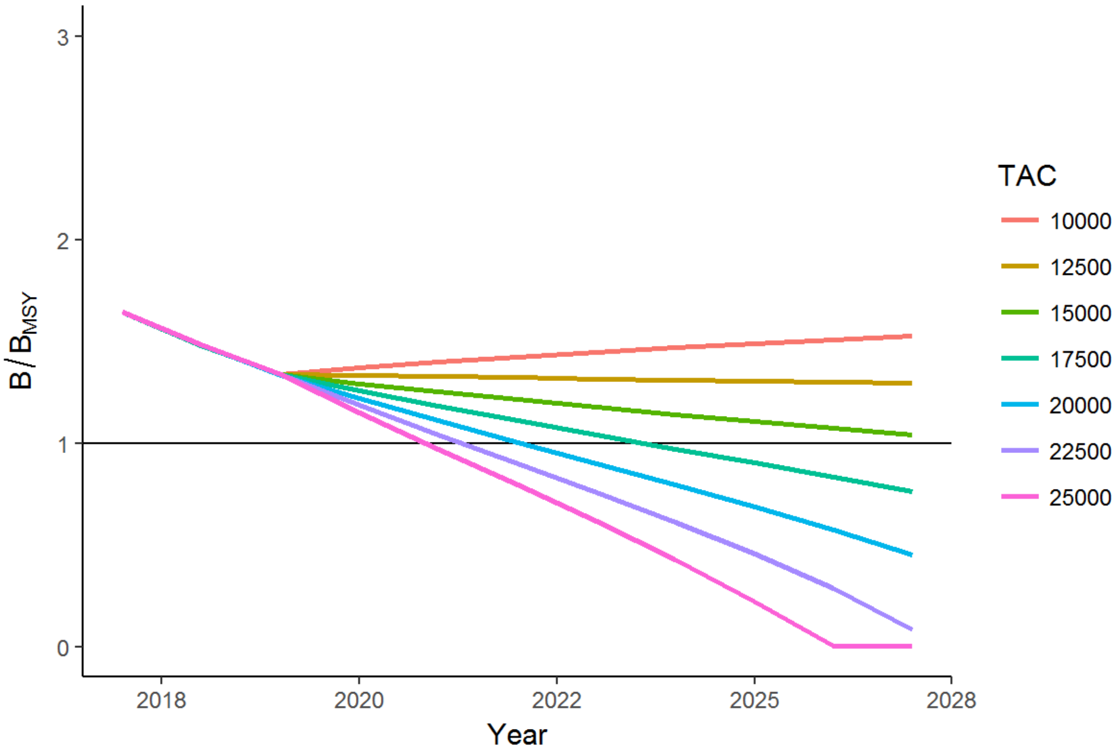

Figure 11. Projections based on the JABBA Reference scenario (S2) for Indian Ocean black marlin for various levels of future catch.