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STOCK ASSESSMENT OF ATLANTIC BLUE MARLIN (*MAKAIRA NIGRICANS*) USING A BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL *JABBA*

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SUMMARY

*Bayesian State-Space Surplus Production Models were fitted to Atlantic blue marlin (*Makaira nigricans*) catch and CPUE data using the open-source stock assessment tool JABBA. The three scenarios (S1_All, S2_drop2 and S3_LL) were based on sensitivity analysis of the initial runs, including the three 'steepness-specific' r input priors and the influence of removing one of 12 candidate CPUE series at a time. The results for the three alternative scenarios estimated MSY between 3195 tons and 3341 tons. Stock status trajectories showed a typical anti-clockwise pattern, moving from initially underexploited through a period of unsustainable fishing, leading to a > 95% probability of stock biomass in 2016 being below levels that can produce MSY. The 2016 fishing mortality rate estimates were close to or exceeding the sustainable exploitation levels that would be required to achieve rebuilding to biomass levels at MSY in the short- to medium term, albeit associated with high uncertainty. Based on multi-model inference from all three scenarios, there is a 97.2% probability that the stock remains overfished and a 40.2% probability that overfishing is still occurring.*

RÉSUMÉ

*Les modèles de production excédentaire état-espace de type bayésien ont été ajustés aux données de capture et de CPUE du makaire bleu de l'Atlantique (*Makaira nigricans*) au moyen de l'outil JABBA d'évaluation des stocks en open source. Les trois scénarios (S1_All, S2_drop2 et S3_LL) étaient basés sur une analyse de sensibilité des scénarios initiaux, incluant les distributions a priori d'entrée spécifiques à la steepness r et l'influence de la suppression de l'une des 12 séries potentielles de CPUE à la fois. D'après ces trois scénarios alternatifs, il a été estimé que la PME oscille entre 3.195 et 3.341 tonnes. Les trajectoires de l'état des stocks présentaient un schéma typique allant dans le sens inverse des aiguilles d'une montre, passant d'un état sous-exploité à une période de pêche insoutenable, conduisant à une probabilité de > 95% que la biomasse du stock en 2016 se situe en dessous des niveaux permettant d'atteindre la PME. Les estimations du taux de mortalité par pêche de 2016 avoisinaient ou dépassaient les niveaux d'exploitation soutenable nécessaires pour atteindre le rétablissement du stock à des niveaux de biomasse correspondant à la PME à court et moyen terme, quoique associés à une incertitude élevée. Sur la base de l'inférence multi-modèles des trois scénarios, il existe une probabilité de 97,2% que le stock reste surexploité et une probabilité de 40,2% que la surpêche ait encore lieu.*

RESUMEN

Los modelos de producción excedente estado-espacio bayesianos se ajustaron a los datos de CPUE y de captura de aguja azul del Atlántico (Makaira nigricans*) utilizando una herramienta de evaluación de stock de fuente abierta JABBA. Los tres escenarios (S1_All, S2_drop2 y S3_LL) se basaron en análisis de sensibilidad de los ensayos iniciales, lo que incluye las tres distribuciones previas de entrada de inclinación específica y la influencia de excluir cada vez una de las 12 series de CPUE candidatas. Los resultados de los tres escenarios alternativos estimaron RMS que oscilaron entre 3.195 y 3.341 t. Las trayectorias del estado del stock mostraban un típico patrón contrario a las agujas del reloj, moviéndose desde subexplotado hasta un periodo de pesca insostenible, que conducía a una probabilidad > 95% de que la biomasa del stock en 2016 se sitúe por debajo de los niveles que permiten el RMS. Las*

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estimaciones de 2016 de la mortalidad por pesca situaban en un nivel cercano o superior a los niveles de explotación sostenible que se requerirían para conseguir la recuperación de los niveles de biomasa hasta niveles en RMS a corto medio plazo, aunque asociadas con un elevado nivel de incertidumbre. Basándose en la inferencia del multi modelo de los tres escenarios, hay una probabilidad del 97,2% de que el stock permanezca sobrepescado y una probabilidad del 40,2% de que se esté produciendo todavía sobrepesca.

KEYWORDS

Billfish, stock status, CPUE fits, biomass dynamic model,
Pella-Tomlinson surplus production function

1. Introduction

In 2006, the International Commission for the Conservation of Atlantic Tunas (ICCAT) carried out a partial stock assessment for Atlantic blue marlin. However, a full stock assessment was only conducted in 2011, which included outputs from a non-equilibrium production model ASPIC and from a statistically integrated model Stock Synthesis The 2011 assessment comprised catch and effort data up to 2009 and estimations of management reference points (ICCAT, 2011). The results from both models indicated that the stock remains overfished and overfishing is occurring. Management benchmarks resulting from two alternative ASPIC models (low and high productivity) revealed that B_{2009}/B_{MSY} was about 0.52 to 0.57 and F_{2009}/F_{MSY} was around 1.33 to 2.19. For the Stock Synthesis model these management reference points were 0.67 for B_{2009}/B_{MSY} and 1.63 for F_{2009}/F_{MSY}. Despite the status of the blue marlin stock is overfished, ICCAT also recognizes the high uncertainty with regard to data and the productivity of the stock.

Here we present stock assessment results for Atlantic blue marlin 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 CPUE time series through 2016. JABBA is a fully documented, open-source software that has been applied in a number of recent ICCAT stock assessments, including south Atlantic blue shark (ICCAT, 2015), western Atlantic sailfish (Mourato and Carvalho, 2017; ICCAT 2016b), Mediterranean albacore (ICCAT, 2017a) south Atlantic swordfish (ICCAT, 2017b) and Atlantic shortfin mako shark stocks (south and north) (Winker et al., 2017; ICCAT, 2017c).

2. Material and Methods

2.1 Fishery data

The ICCAT secretariat estimates catch for many fleets and nations based on the best available information. Fishery catch data from 1959-2016 for assessing Atlantic blue marlin were obtained from the analysis carried out during the data preparatory meeting in March 2018 (ICCAT, 2018) (**Figure 1**). 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 cover a variety of fishing fleets, including longline (LL), recreational (Rec) and artisanal drift gillnet (Gil) fisheries across the Atlantic Ocean. In the present analysis all 12 standardized CPUE series from Japan (LL), United States (LL & Rec), Venezuela (LL, Rec & Gil) Taiwan (LL, 3-time block), Brazil (LL & Rec) and Ghana (Gil), which have been identified as candidate input for the 2018 ICCAT blue marlin assessment (ICCAT, 2018) (**Figure 2**).

2.2 JABBA stock assessment model

This stock assessment is implemented using the Bayesian state-space surplus production model framework JABBA, version v1.1 (Winker et al., 2018a). JABBA 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. A full JABBA model description, including formulation and state-space implementation, prior specification options and diagnostic tools is available in Winker *et al.* (2018a).

Initial trials considered three alternative specifications of the Pella-Tomlinson model type based on different three sets of *r* priors and fixed input values of B_{MSY}/K. The input *r* priors were objectively derived from age-structured model simulations (see details in Winker et al. 2018b), 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 = 0.6), while admitting reasonable uncertainty about the natural mortality *M*. Based on sensitivity analysis of the initial runs, including the three 'steepness-specific' *r* input priors and the influence of removing one CPUE series at a time (results not shown here), the following three specific scenarios were considered, which corresponded to steepness reference case of h = 0.5 with an associated lognormal *r* prior of log(*r*) ~ $N(log(0.098),0.182)$ and a fixed input value of B_{MSY}/K = 0.36:

- **S1_All** (*h = 0.5*) - a base case model including all 12 CPUE series;
- **S2_drop2** (*h = 0.5*) - excluding Taiwan-LL late and United States-Rec and;
- **S3_LL** (*h = 0.5*) - including only CPUE from longline fleets with exclusion of all Taiwan-LL CPUE series.

For *K*, we assumed a vaguely informative lognormal prior with a mean 50,000 metric tons and CV of 200%. Initial depletion lognormal prior ($\varphi = B_{1959}/K$; for details see Winker et al., 2018a) was inputted with mean = 1 and CV of 25%. 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. In this study, two MCMC chains were used. The model was run for 30,000 iterations, sampled with a burn-in period of 5,000 for each chain. Basic diagnostics of model convergence included visualization of the MCMC chains throughout trace-plots.

To evaluate CPUE fits, the model predicted CPUE indices were compared to the observed CPUE. JABBA residual plots were also examined, and the randomness of model residuals was evaluated by means of the Root-Mean-Squared-Error (RMSE). Finally, to verify systematic bias in the estimation of *B* or *F*, we also performed a retrospective analysis for each scenario, by removing one year at a time sequentially (n=8) and predicting the stock status in the form of B/B_{MSY} and F/F_{MSY} trajectories.

3. Results and Discussion

The visual inspection of trace plots of the key model parameters showed good mixing of the two chains (i.e., moving around the parameter space), also indicative of convergence of the MCMC chains and that the posterior distribution of the model parameters was adequately sampled with the MCMC simulations (see **Appendix A**).

Model residuals indicated some discrepancies between CPUE series and model predictions, especially for Venezuelan, Brazilian and Ghana fleets, which might be characterized by high variation (**Figure 3**). The RMSE values indicated that the goodness-of-fit was comparable among S1_All and S2_drop2 (~54-58%). On the other hand, when only CPUE from longline fleets was included (S3_LL) in the model, the RMSE was reduced to around 37% (**Figure 3**). The predicted CPUE indices from the models fits were compared to the observed CPUE for each scenario (**Figure 4, 5** and **6**). The model fits for blue marlin CPUEs indicated that there was a lack of fit from longline fisheries of Taiwan, Brazil and Venezuela and from Brazilian and Venezuelan recreational fisheries and Ghana gillnet fishery (**Figure 4, 5** and **6**).

Plots of posterior densities together with prior densities are depicted in **Figures 7-9**. Summaries of posterior quantiles for parameters and management quantities of interest are presented in **Table 1**. The median of marginal posterior for *r* varied between 0.089 and 0.1 among scenarios. On comparison between posterior and prior distributions for *r*, S1_All and S2_drop2 produced the best agreement, while the *r* posterior density for S3_LL was located higher and lower relative to the prior. As a result, the *r* posterior densities for S1_All and S2_drop2 were located in closer proximity to each other than their respective posteriors, suggesting that the data hold information about the stock's productivity. Scenarios S1_All and S2_drop2 resulted in more productive stock compared to S3_LL, which showed a notable divergence from the prior. The median of marginal posterior for *K* varied between 74,809 metric tons (S1_All) and 99,506 metric tons (S3_LL). It was also noted that posterior distributions for K was narrow in comparison to their priors, which indicates that input data was very informative for all fitted models. The marginal posteriors for initial depletion were similar for all scenarios with median estimates varying from 0.915 to 0.937 **(Table 1**). Posterior densities were relatively narrow in relation to their priors, indicating some consistence and informative data for this estimate (**Figures 7-9**).

The *MSY* estimates showed little variation, ranging from 3,195 to 3,341 metric tons among all three scenarios. The B_{MSY} estimates were slightly different among scenarios, with smaller value for scenario S1_All (median= 30,532 t) in comparison to the scenarios S2_drop2 and S3_LL (median= 32,059 t and 35,824 t, respectively) **(Table 1**). As expected, the F_{MSY} estimates were very similar (close to 0.1) among scenarios **(Table 1**), since that inflection point of the surplus production function were the same for the three scenarios (B_{MSY}/K = 0.36).

In general, all scenarios presented similar trends for the B/B_{MSY} and F/F_{MSY} (**Figure 10**). The trajectory of B/B_{MSY} showed a sharp decrease until middle of 1970s to an overfished status followed by a decreasing trend until 2000. Since the early 2000s the relative biomass has remained stable at levels below B_{MSY} until 2016. The F/F_{MSY} trajectory showed an increasing trend since of beginning of time series, crossing F_{MSY} in the middle of 1980s, followed by a decreasing trend after 2000s, but always higher than F_{MSY} until the last year (**Figure 10**). However, results from scenario S1_All are slightly more optimistic in comparison to the other scenarios (**Figure 10**).

Individual Kobe biplots for all scenarios revealed similar trends among the fitted models, showing a relatively anti-clockwise pattern with the stock status moving from underexploited through a period of unsustainable fishing to the overexploited phase since middle 1980s (**Figure 11**). However, the resulting stock status posteriors for 2016 showed slightly differences between S1_All and the other scenarios, with 49.9% support for an overfished state (red), 1.3% for a sustainable stock (green) and 48.8% (yellow) of the posterior pairs. All other scenarios were a little more optimistic regarding stock status for 2016, with more than 39-44% probability of the posterior pairs falling within overfished area (red) and around 54-58% in yellow phase (**Figure 11**). A retrospectives analysis conducted over nine sequential years for each scenario is depicted in **Figures 12-14.** Results showed no evidence of strong retrospective patterns and were very consistent among scenarios (**Figures 12-14**). This indicated that all runs were robust in terms of similar stock status (F/F_{MSY}; B/B_{MSY}) and *MSY* and thus can be considered suitable for projections. Finally, a Kobe phase plot is presented to provide multi-model inference based on combined of all three scenarios (**Figure 15)**, which predicts with 97.2% probability that the stock remains overfished and 40.2% probability that overfishing is still occurring.

In conclusion, the results of this study provide evidence that the Atlantic blue marlin biomass remained below B_{MSY} in 2016. In addition, fishing mortality rate in 2016 likely remained close to or above sustainable levels that would be required to achieve rebuilding to biomass levels at MSY in the short- to medium term. However, it is important to highlight that there is considerable uncertainty in the estimated fishing mortality rate levels

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Table 1. 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 Atlantic blue marlin.

	S1_All			S2_drop2			S3_LL		
Estimates	Median	2.50%	97.50%	Median	2.50%	97.50%	Median	2.50%	97.50%
K	84809	65741	114413	89049	67972	118676	99506	74200	136983
r	0.1	0.075	0.131	0.098	0.073	0.13	0.089	0.065	0.12
y (*psi*)	0.915	0.677	1.107	0.923	0.72	1.11	0.937	0.731	1.122
σ_{proc}	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
F_{MSY}	0.104	0.078	0.137	0.103	0.076	0.136	0.093	0.068	0.125
B_{MSY}	30532	23668	41190	32059	24471	42725	35824	26713	49316
MSY	3195.7	2704	3749.7	3298.5	2776	3864.4	3341	2760	3983.3
B_{1959}/K	0.914	0.677	1.038	0.924	0.728	1.041	0.937	0.742	1.044
B_{2016}/K	0.232	0.143	0.342	0.236	0.156	0.359	0.228	0.142	0.353
$B_{2016}/B_{\mathrm{MSY}}$	0.643	0.398	0.949	0.655	0.432	0.998	0.635	0.394	0.981
$F_{2016}/F_{\mathrm{MSY}}$	1	0.645	1.577	0.945	0.605	1.478	0.964	0.587	1.599

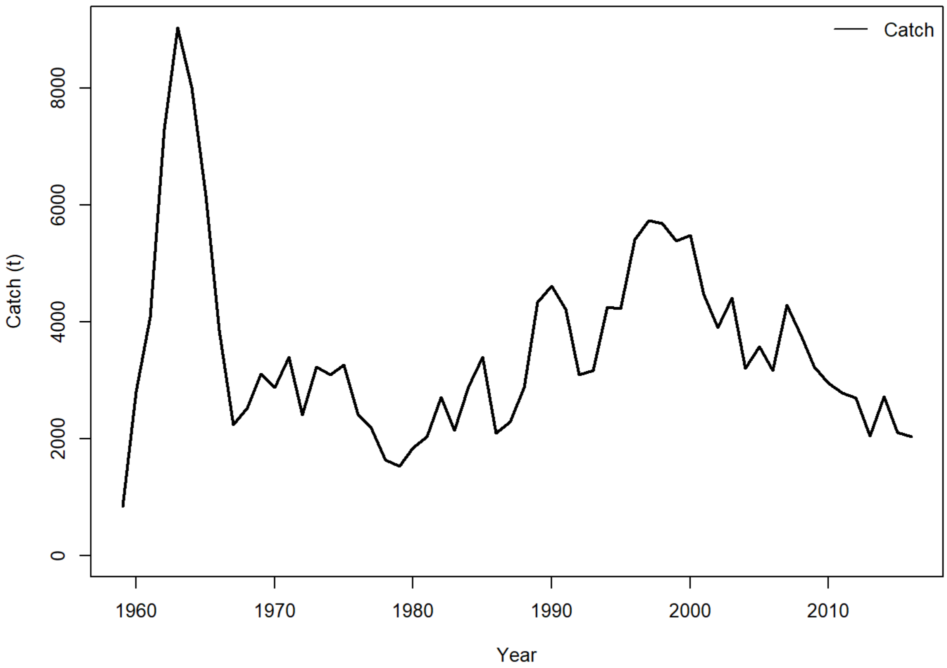

Figure 1. Time-series of catch in metric tons (t) for the blue marlin in the Atlantic Ocean.

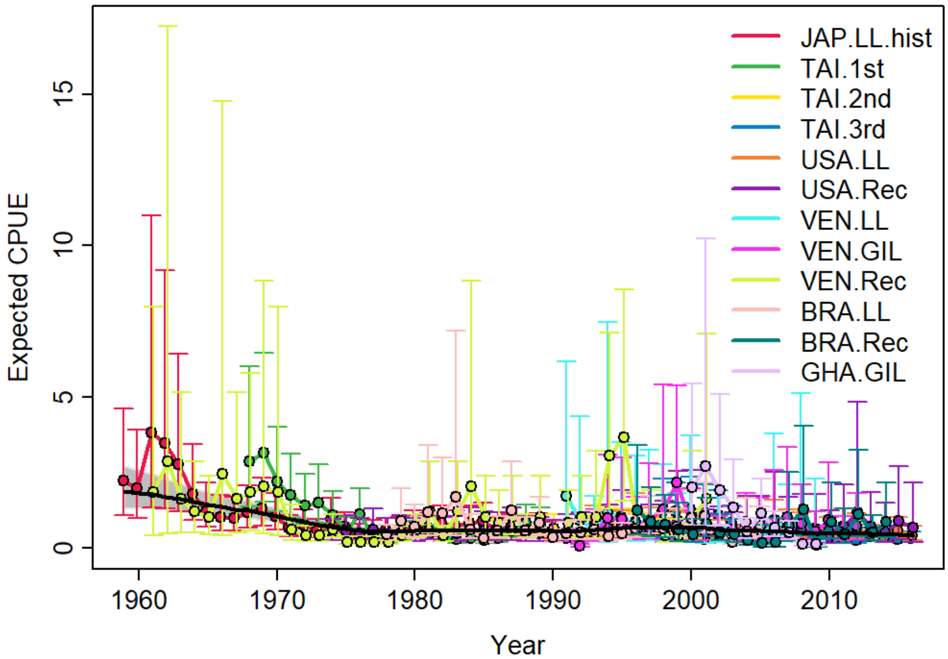

Figure 2. Time-series of 12 standardized CPUE series for blue marlin in the Atlantic Ocean.

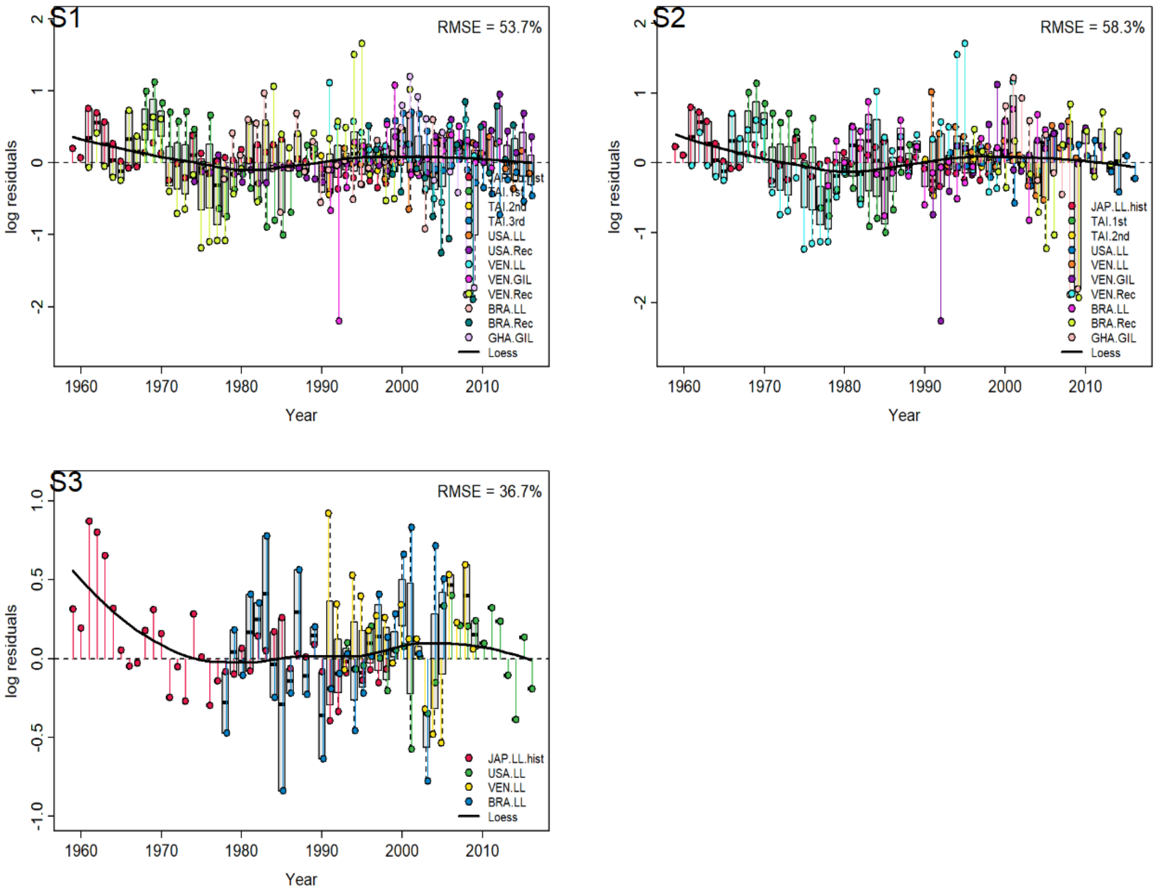

Figure 3. JABBA residual diagnostic plots for alternative sets of CPUE indices examined for each scenario for the Atlantic blue marlin. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals.

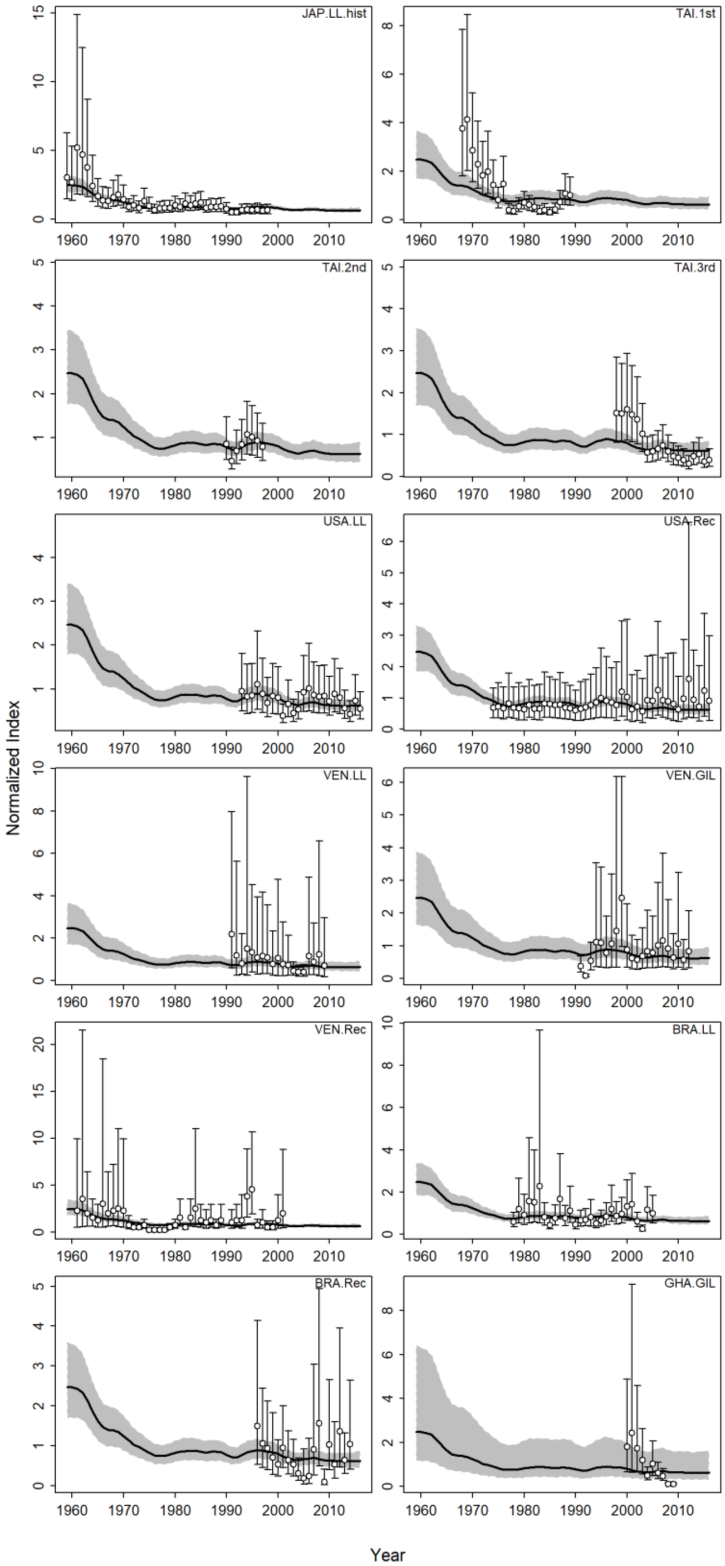

Figure 4. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of blue marlin in the Atlantic Ocean for the Bayesian state-space surplus production model JABBA for scenario S1_All. Shaded grey area indicates 95% credibility intervals.

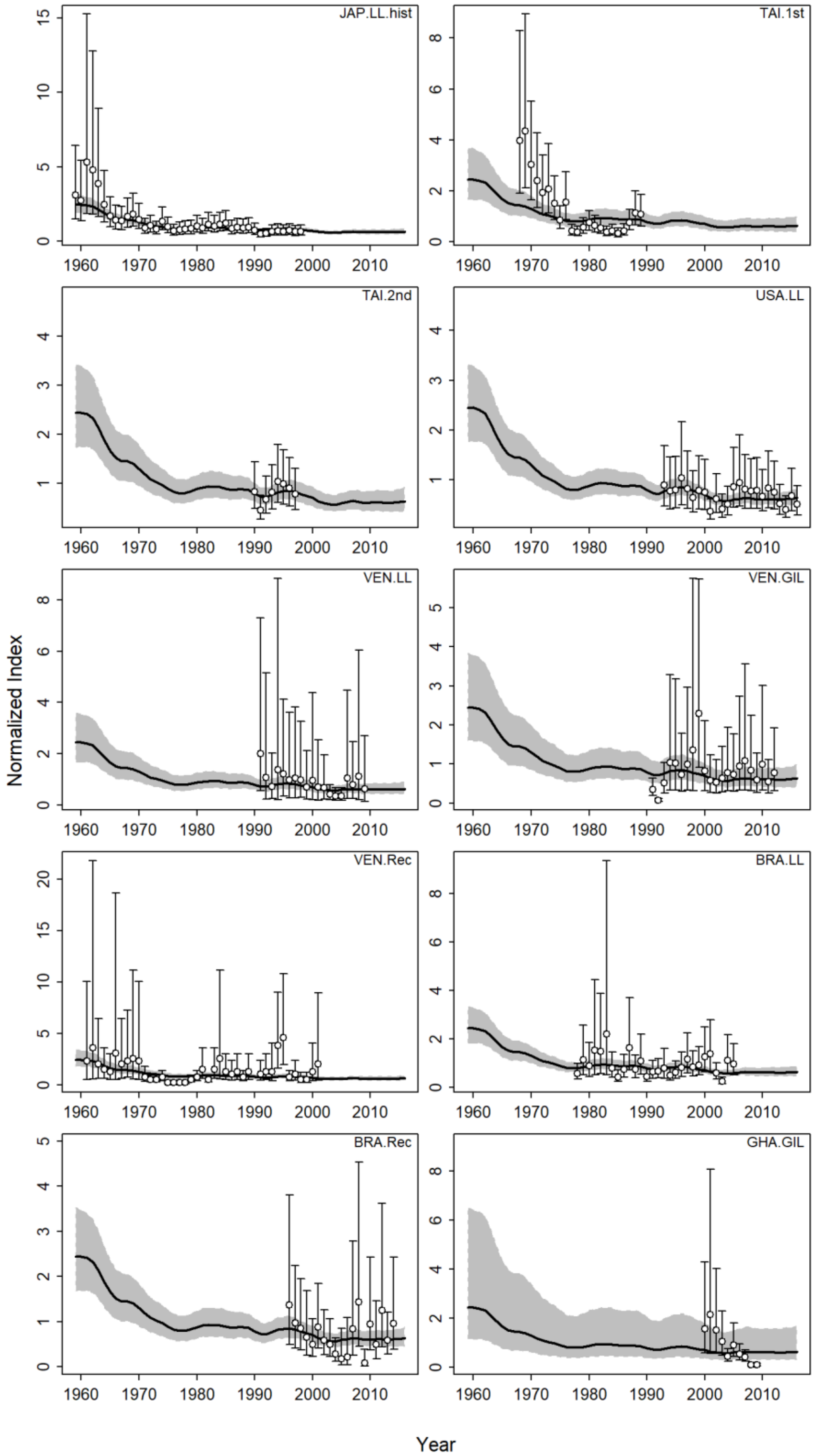

Figure 5. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of blue marlin in the Atlantic Ocean for the Bayesian state-space surplus production model JABBA for scenario S2_drop2. Shaded grey area indicates 95% credibility intervals.

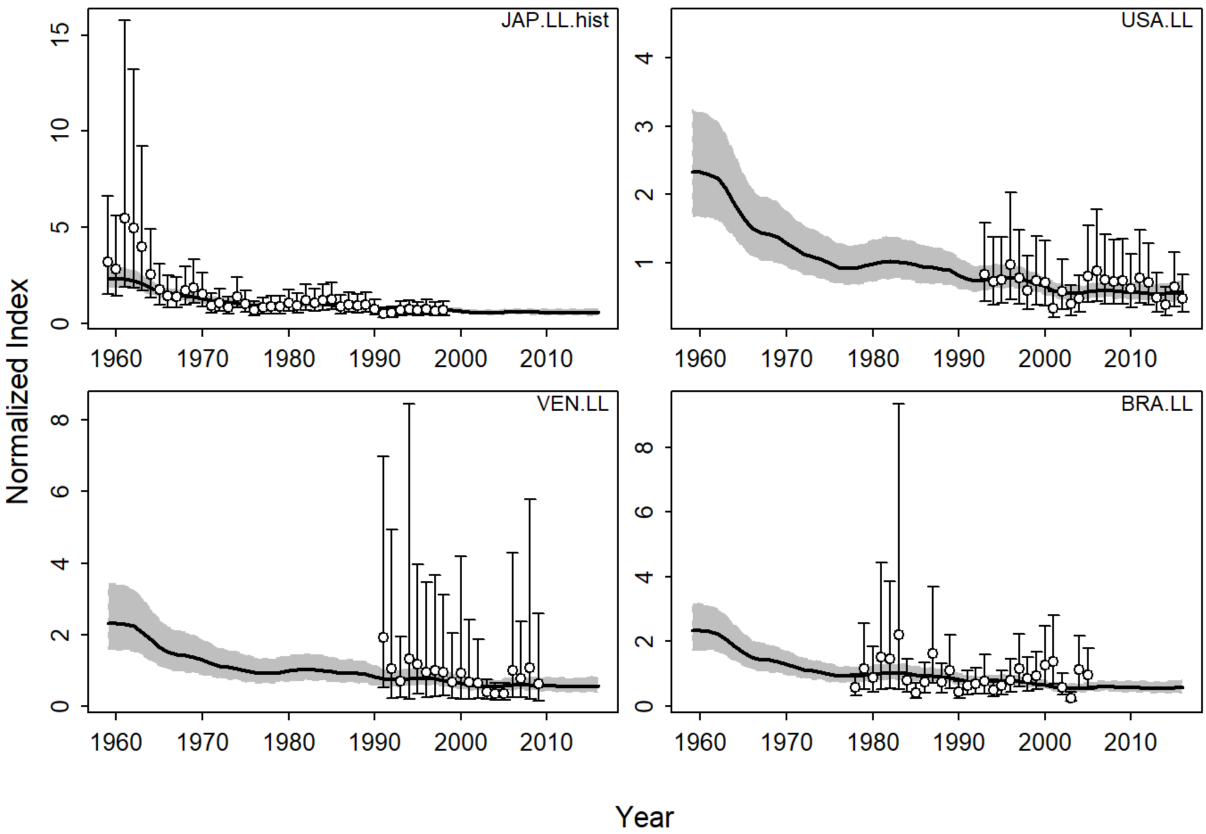

Figure 6. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of blue marlin in the Atlantic Ocean for the Bayesian state-space surplus production model JABBA for scenario S3_LL. Shaded grey area indicates 95% credibility intervals

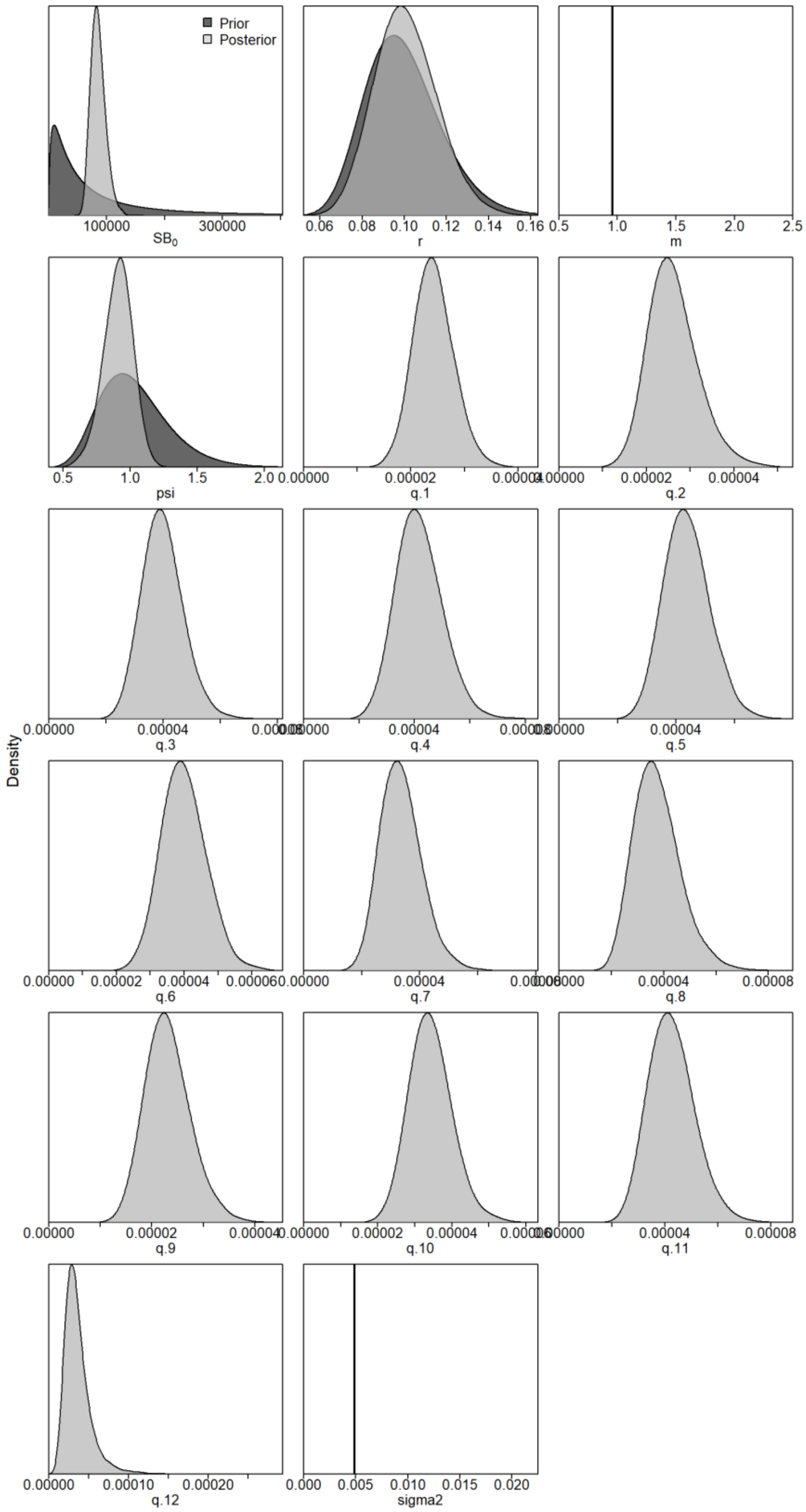

Figure 7. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S1_All) for blue marlin in the Atlantic Ocean.

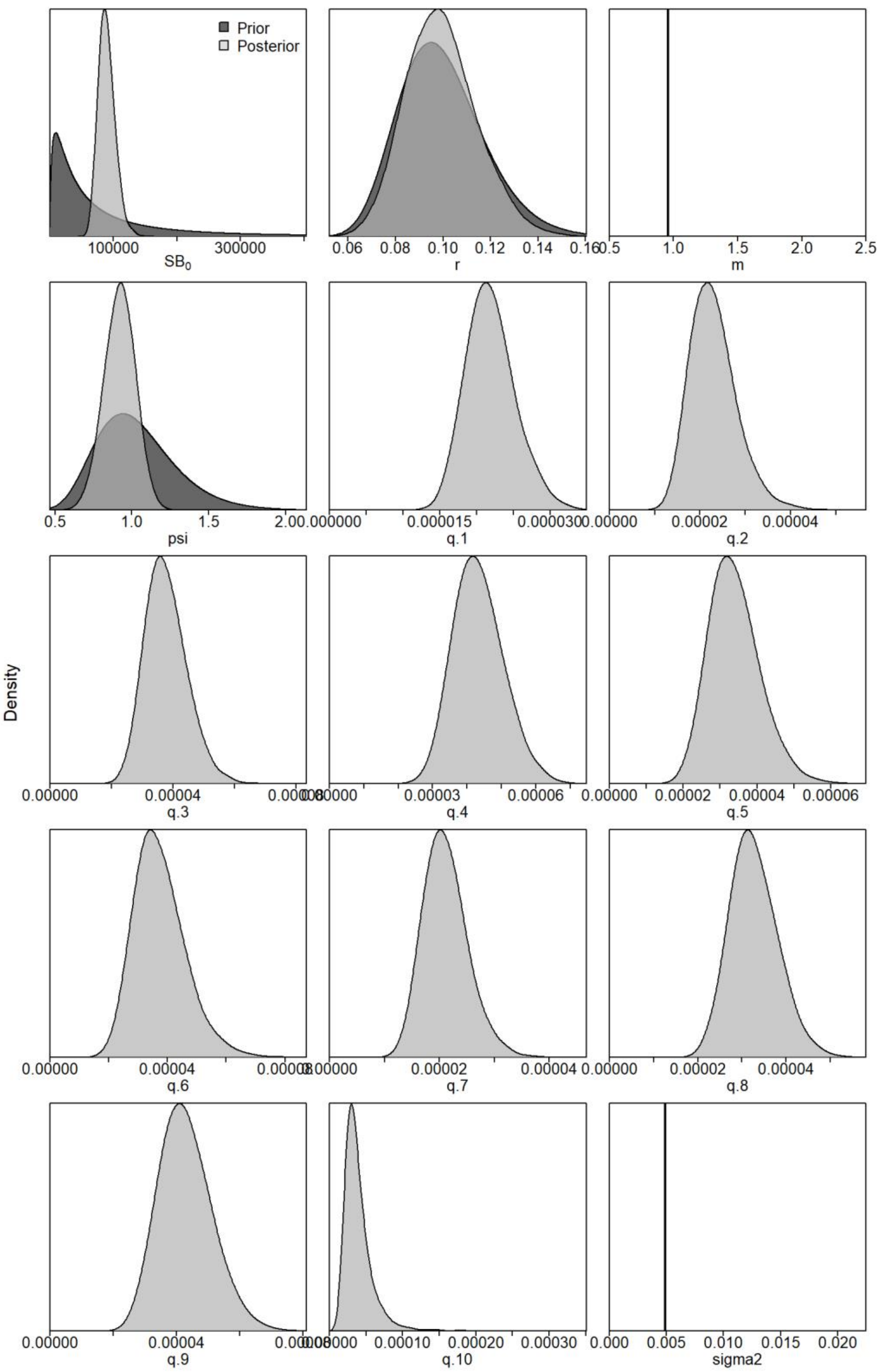

Figure 8. Prior and posterior distribution of various model and management parameters for the Bayesian state-space surplus production model (scenario S2_drop2) for blue marlin in the Atlantic Ocean.

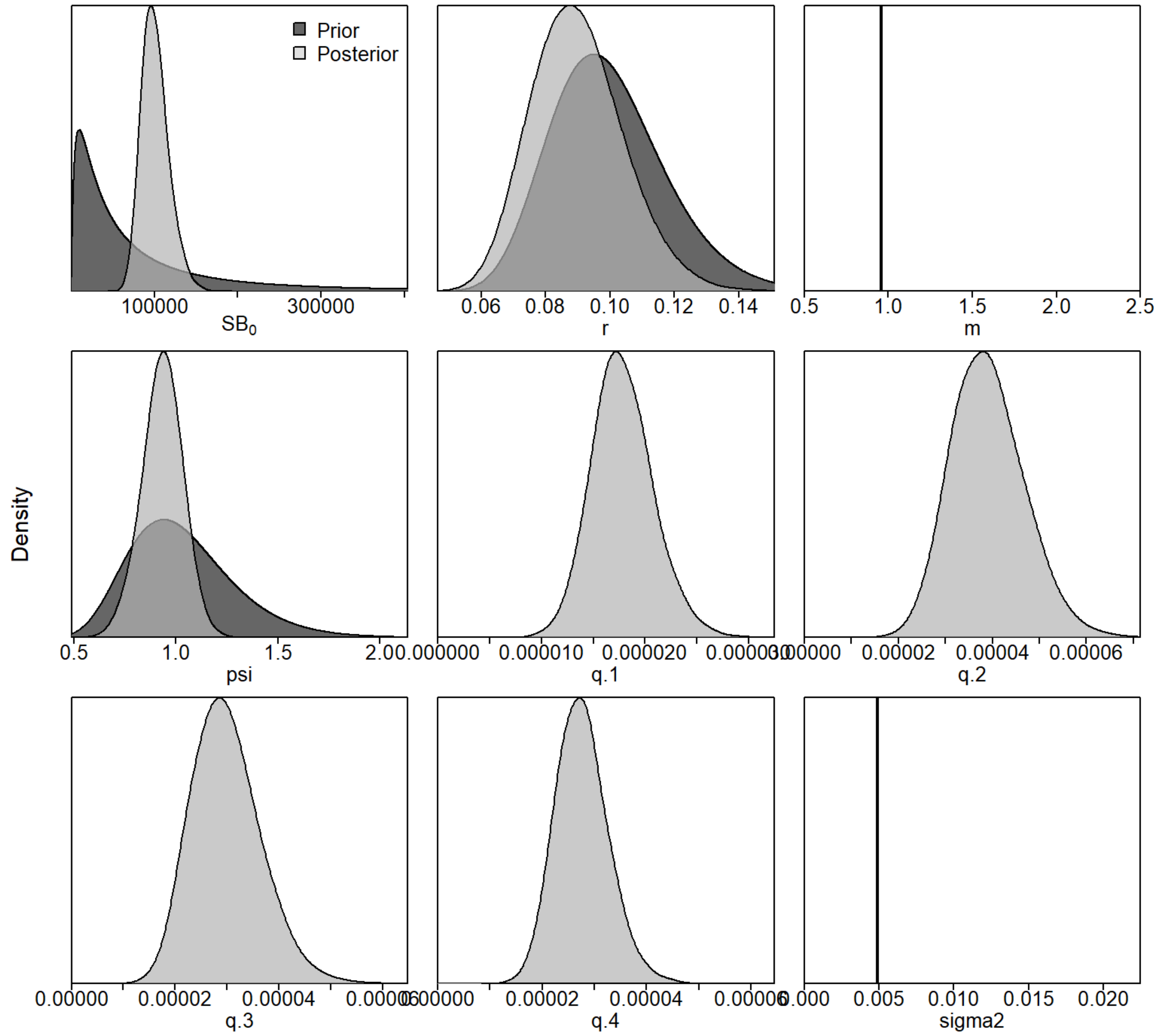

Figure 9. Prior and posterior distribution of various model and management parameters for the Bayesian state-space surplus production model (scenario S3_LL) for blue marlin in the Atlantic Ocean.

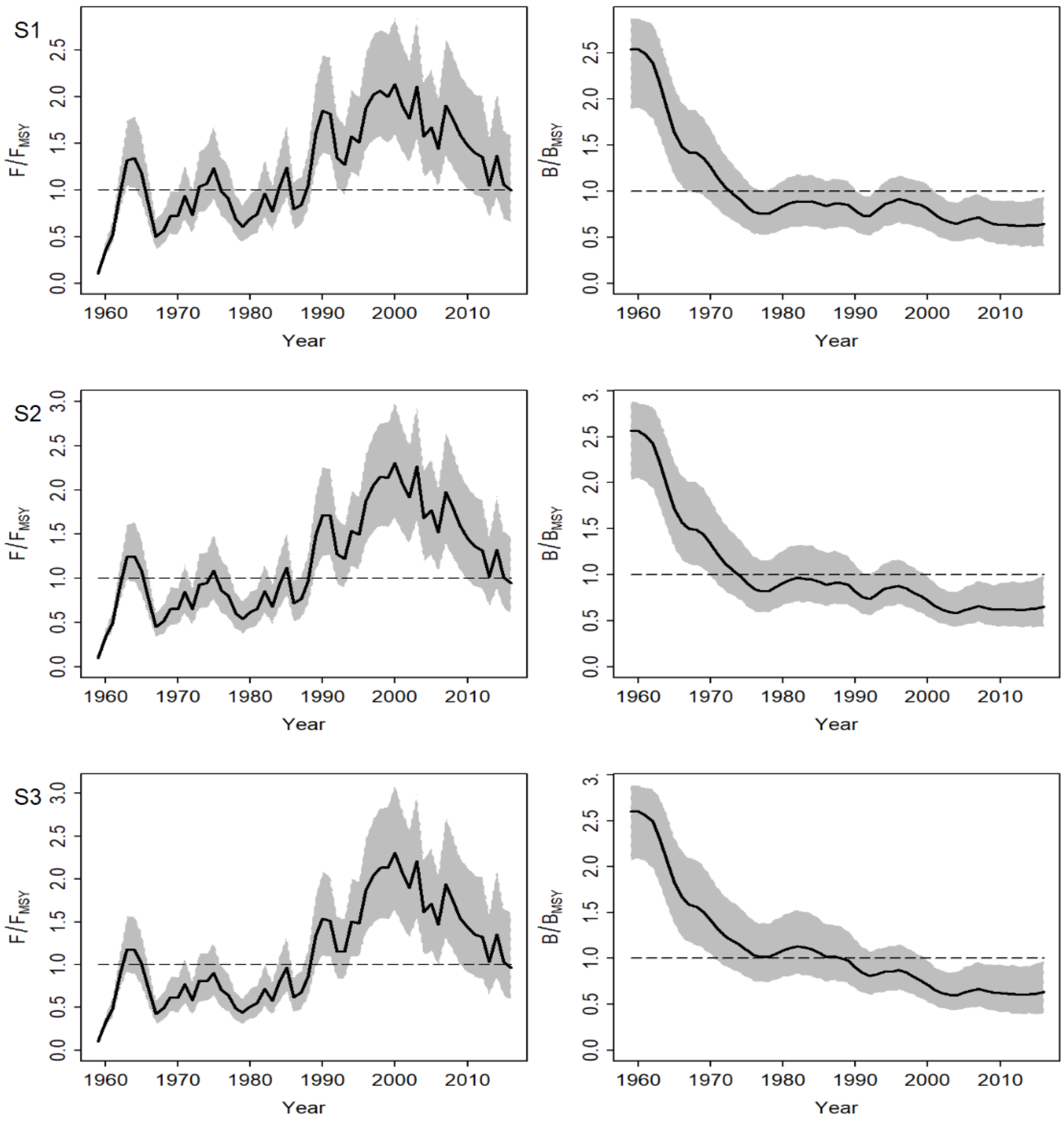

Figure 10. Trends in harvest rate relative to F_{MSY} and biomass relative to B_{MSY} for each scenario from the Bayesian state-space surplus production model fits to Atlantic blue marlin. Shaded grey area indicates 95% credibility intervals

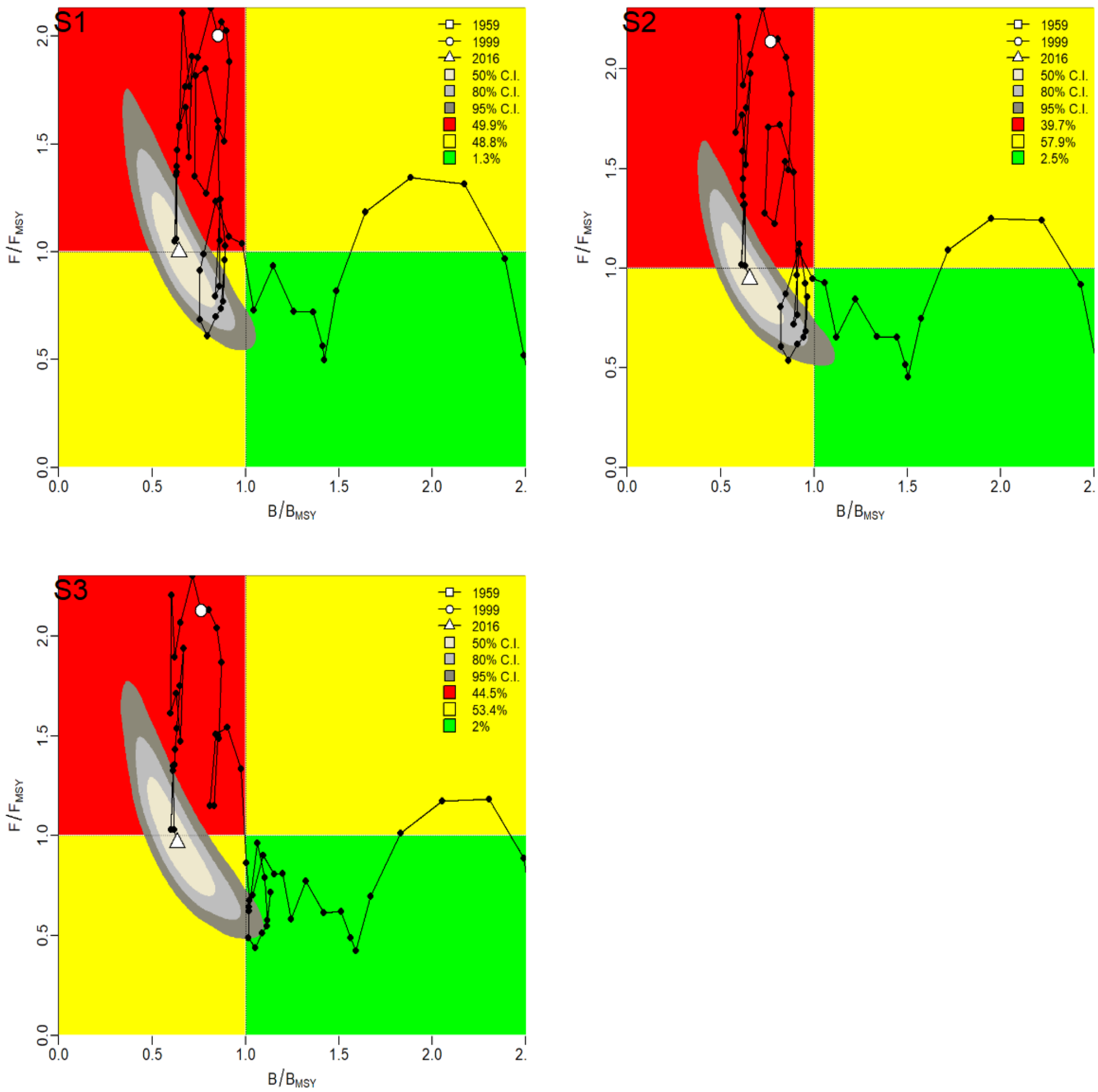

Figure 11. Kobe phase plot showing estimated trajectories (1959-2016) of B/B_{MSY} and F/F_{MSY} for for the Bayesian state-space surplus production model for the Atlantic blue marlin. Different grey shaded areas denote the 50%, 80%, and 95% credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

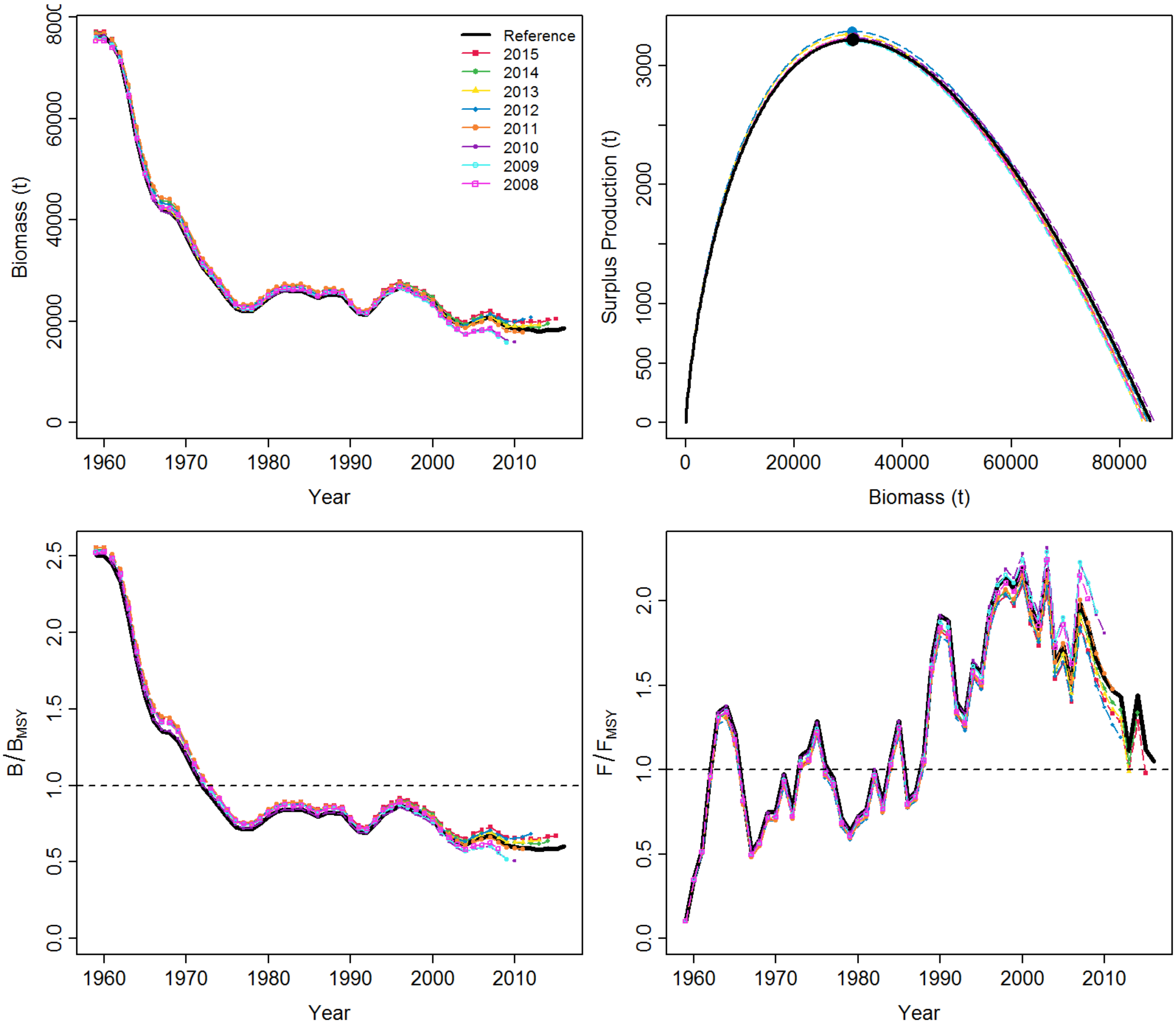

Figure 12. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic blue marlin (Scenario S1_All). The label "Reference" indicates the basecase model fits to the entire time series 1959-2016. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2008.

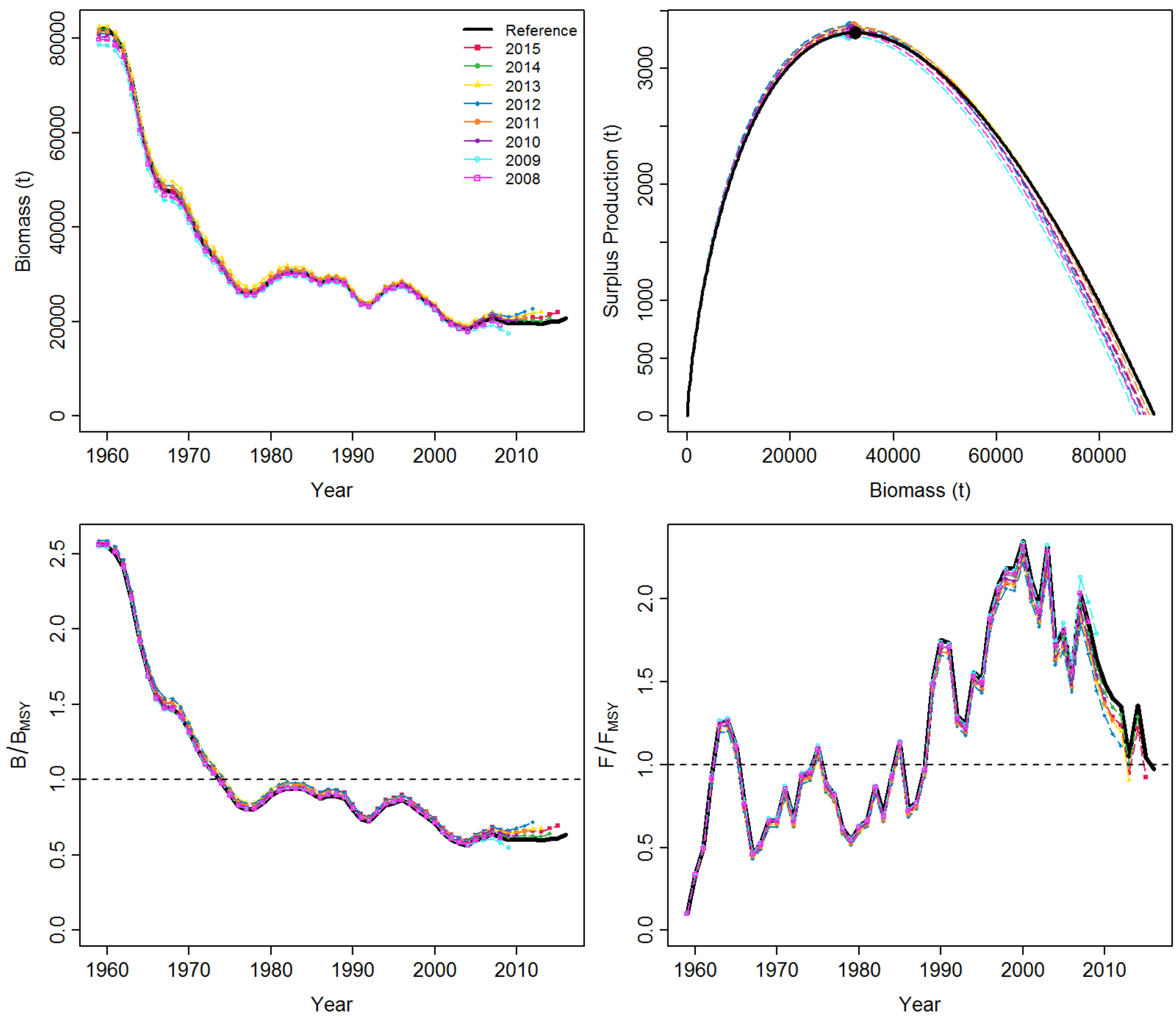

Figure 13. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic blue marlin (Scenario S2_drop2). The label "Reference" indicates the basecase model fits to the entire time series 1959-2016. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2008.

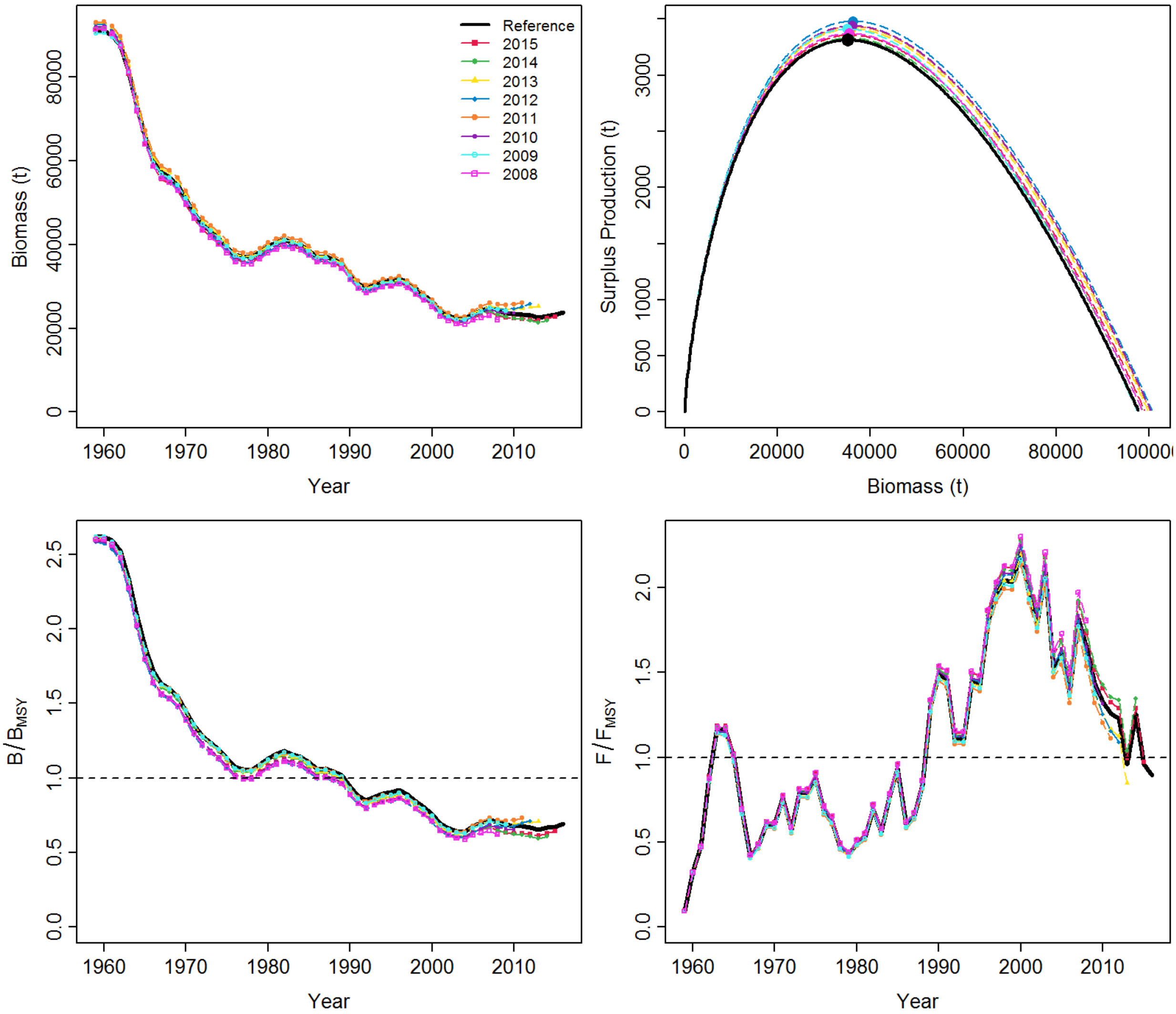

Figure 14. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic blue marlin (Scenario S3_LL). The label "Reference" indicates the basecase model fits to the entire time series 1959-2016. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2008.

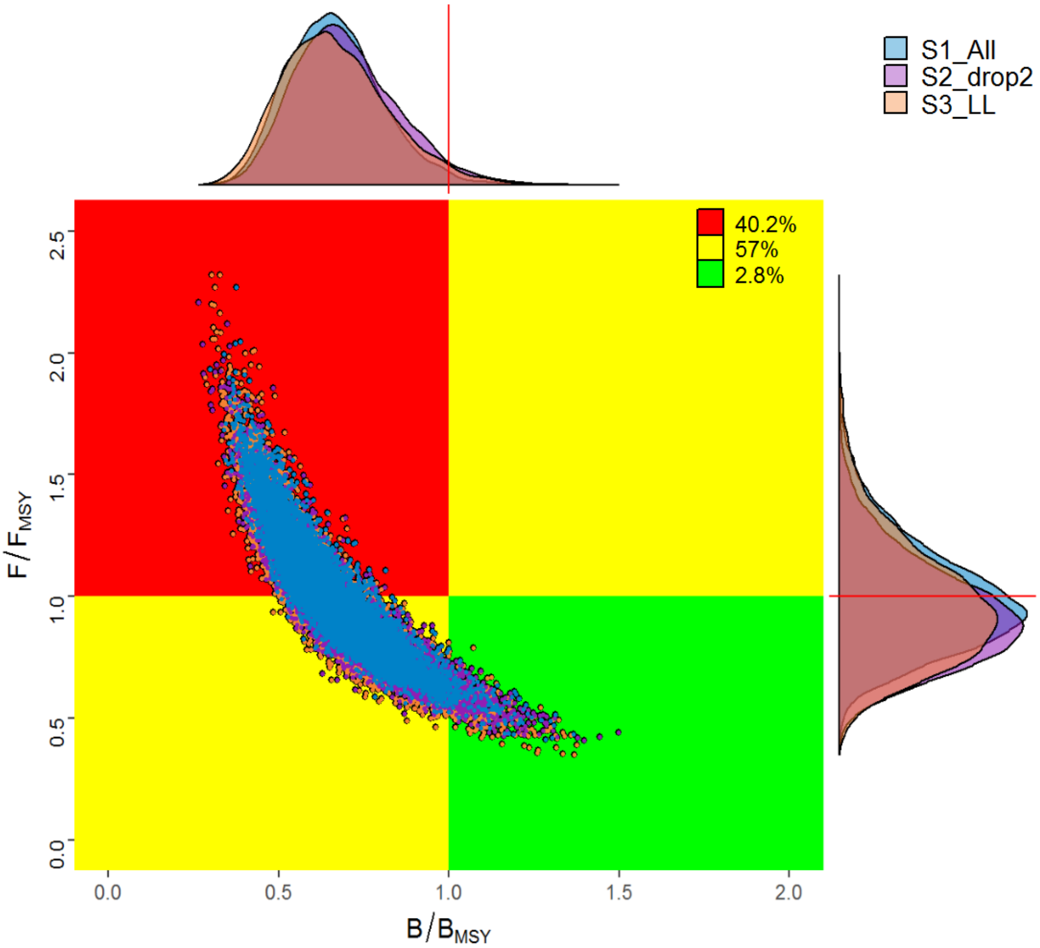

Figure 15. Kobe phase plot showing the combined posteriors of B/B_{MSY} and F/F_{MSY} (1959-2016) from all three scenarios runs using the 'Kobe' library in FLR (Kell et al., 2007). The probability of terminal year points falling within each quadrant is indicated in the figure legend.

Appendix A

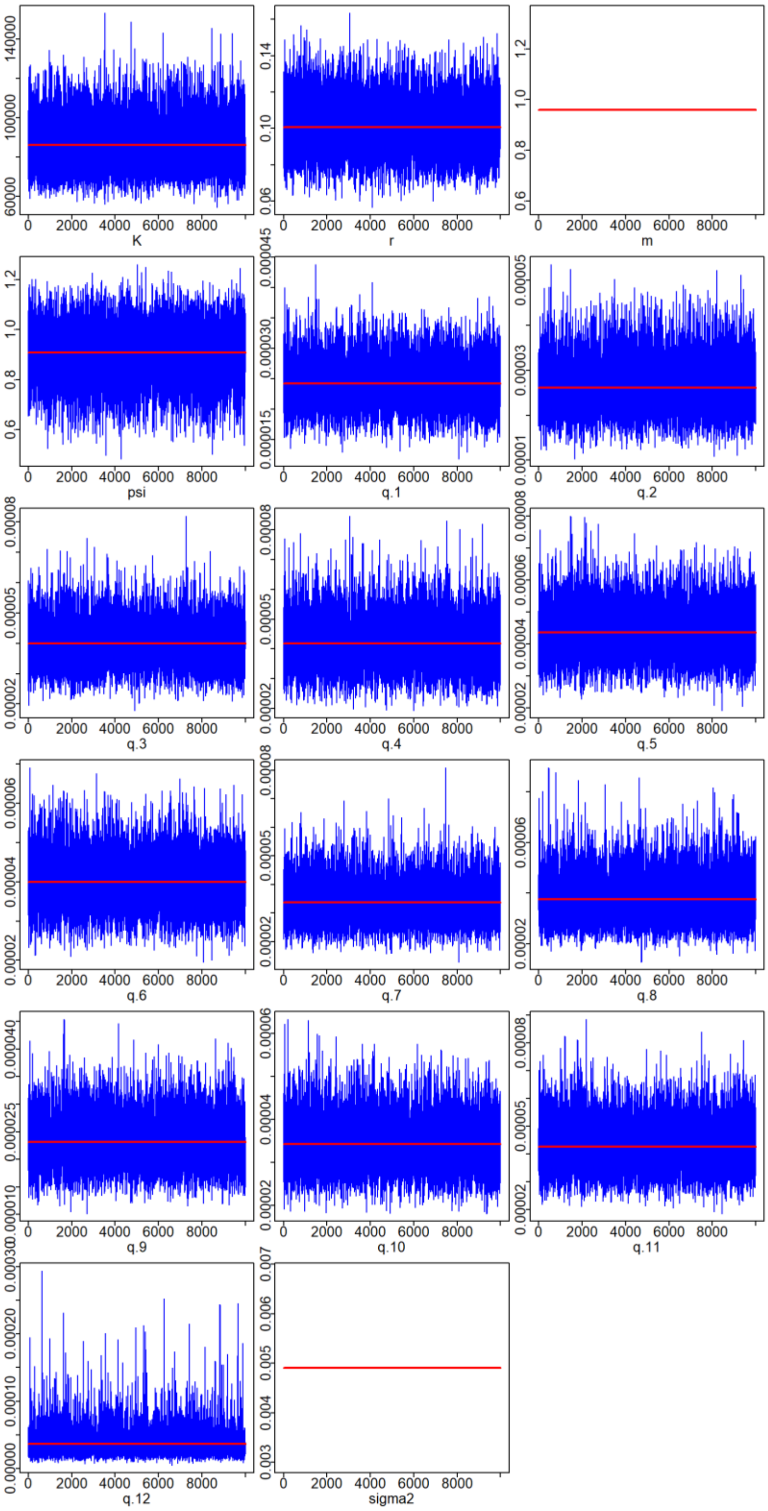

Figure A1. Trace plots for the model (scenario S1_All) parameter drawn from MCMC samples in the Bayesian state-surplus production model for the Atlantic blue marlin.

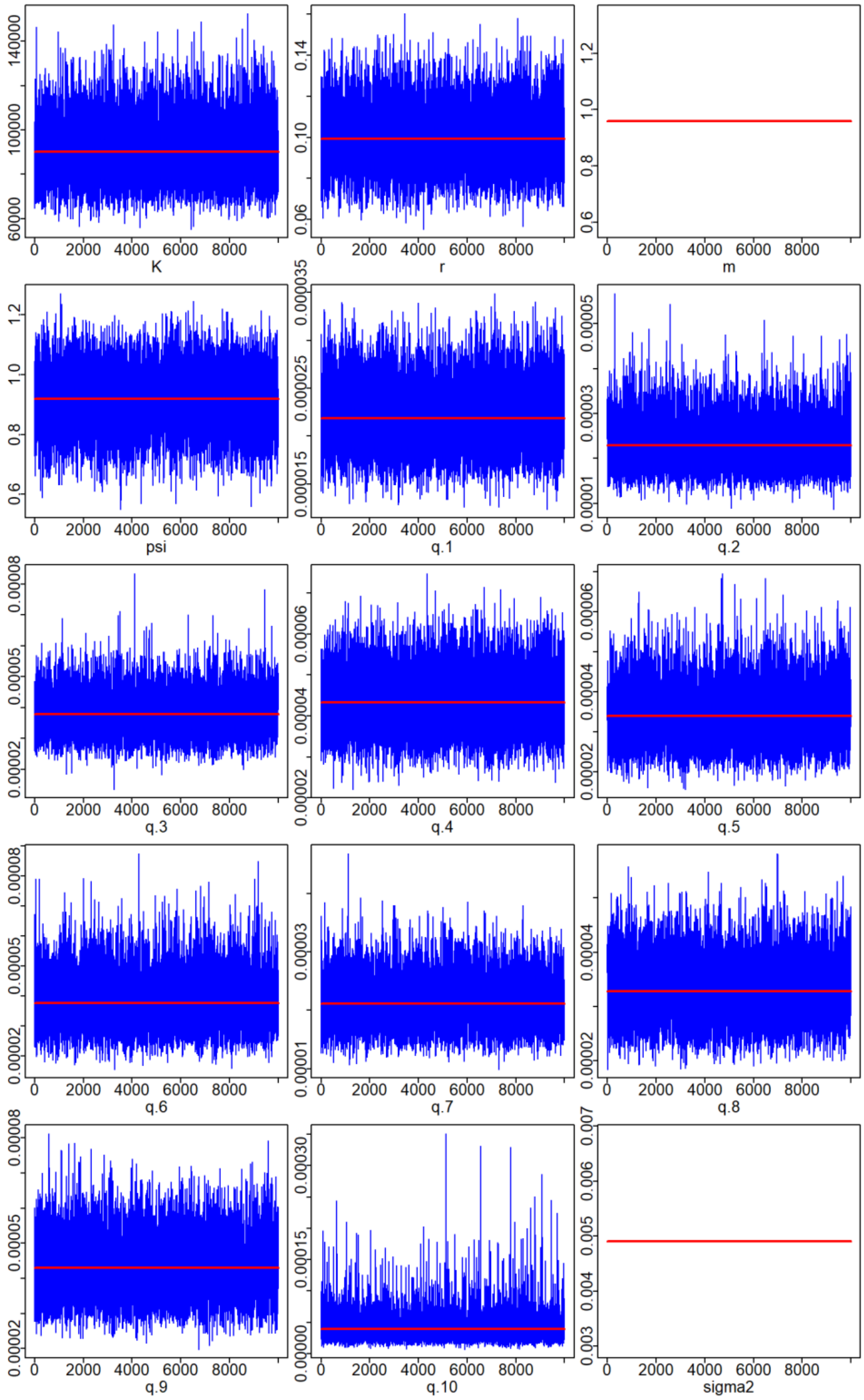

Figure A2. Trace plots for the model (scenario S2_drop2) parameter drawn from MCMC samples in the Bayesian state-surplus production model for the Atlantic blue marlin.

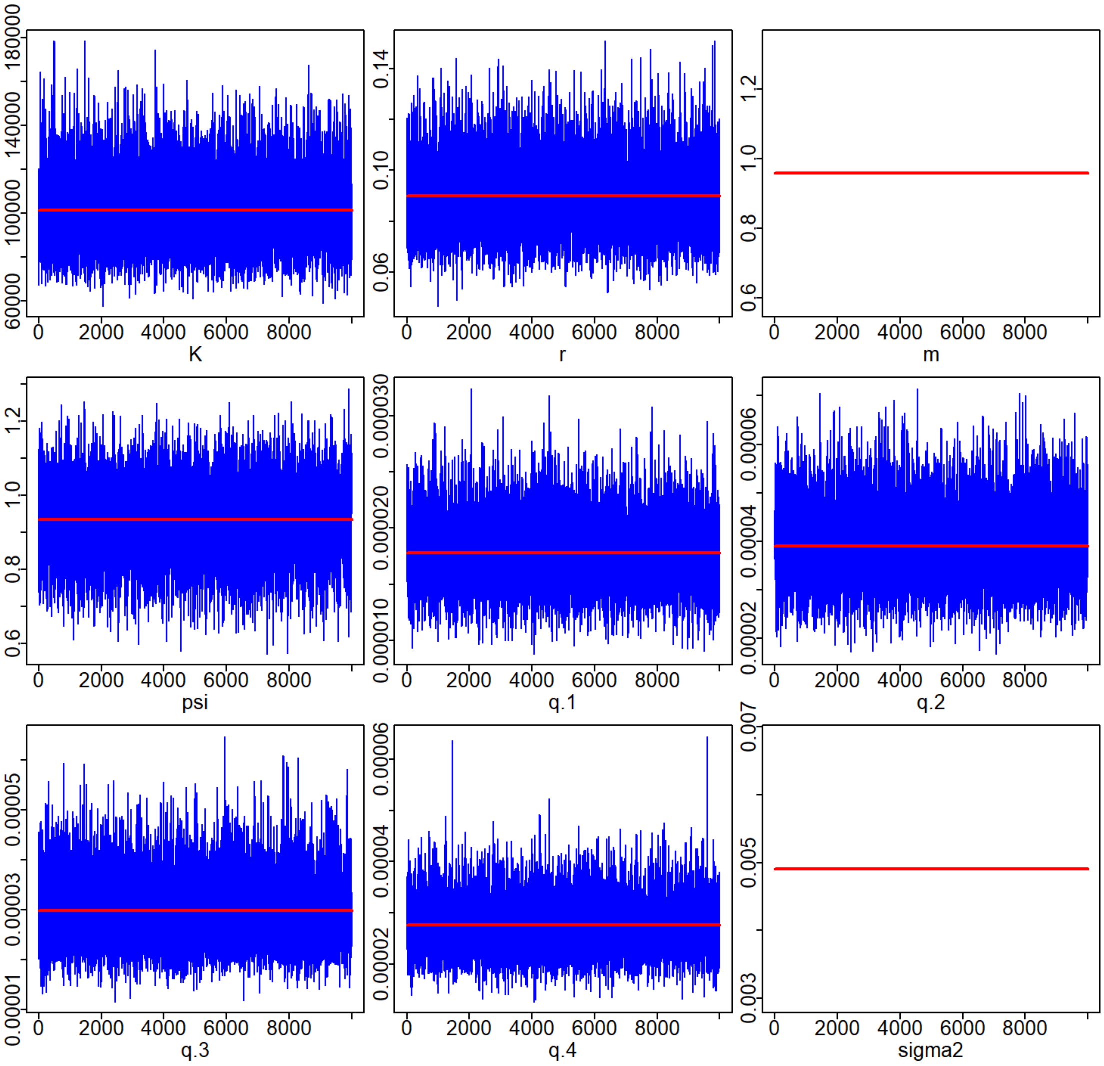

Figure A3. Trace plots for the model (scenario S3_LL) parameter drawn from MCMC samples in the Bayesian state-surplus production model for the Atlantic blue marlin.