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ATLANTIC YELLOWFIN TUNA STOCK ASSESSMENT: AN IMPLEMENTATION OF BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL USING JABBA

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SUMMARY

Bayesian State-Space Surplus Production Models were fitted to yellowfin tuna catch and standardized catch-per-unit-effort (CPUE) data using the open-source stock assessment tool JABBA. Here, we present results from six scenarios (base case model and S1-S5).These scenarios corresponded to combinations of different CPUEs associated with three alternative r prior and shape parameter m parametrizations of the Pella-Tomlinson model. All six scenarios showed similar stock status trajectories that resembled the typical characteristics of a one-way downhill trip, with most recent fishing mortality and the stock's biomass estimated at around levels that can produce MSY. These stock status estimates were, however, associated with very high uncertainty, which may be partially explained by the lack of contrast in the continuously declining biomass trend containing limited information about productivity. Based on multi-model inference from the four final scenarios selected for scientific advice (Base Case, S2, S3 and S5), there is a 54.9% probability that the stock is overfished and a 51.4% 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 capture par unité d'effort standardisée (CPUE) de l'albacore au moyen de l'outil JABBA d'évaluation des stocks en open source. Nous présentons ici les résultats de six scénarios (cas de base du modèle et S1-S5). Ces scénarios correspondaient à des combinaisons de différentes CPUE associées à trois paramétrisations alternatives du prior r et du paramètre de forme m du modèle de Pella-Tomlinson. Les six scénarios présentaient des trajectoires similaires de l'état du stock qui ressemblaient aux caractéristiques typiques d'une descente à sens unique, la mortalité par pêche la plus récente et la biomasse du stock étant estimées à des niveaux proches de ceux qui peuvent produire la PME. Ces estimations de l'état des stocks étaient toutefois associées à une très grande incertitude, qui pourrait s'expliquer en partie par l'absence de contraste dans la tendance à la baisse continue de la biomasse, qui contient peu d'informations sur la productivité. D'après l'inférence multi-modèles des quatre scénarios finaux sélectionnés pour l'avis scientifique (cas de base, S2, S3 et S5), il y a une probabilité de 54,9 % que le stock est surexploité et une probabilité de 51,4% que la surpêche se poursuive.

RESUMEN

Los modelos de producción excedente estado-espacio bayesianos se ajustaron a los datos de captura y de CPUE estandarizada de rabil utilizando una herramienta de evaluación de stock de fuente abierta JABBA. En este documento se presentan resultados de seis escenarios (caso base del modelo y S1-S5). Estos escenarios corresponden a combinaciones de CPUE diferentes asociadas con tres parametrizaciones alternativas de la distribución a priori para r y del parámetro de forma m del modelo Pella-Tomlinson. Los seis escenarios mostraban trayectorias del estado del stock similares a las características típicas de un viaje cuesta abajo sin retorno, con la mortalidad por pesca y la biomasa del stock más recientes estimadas en torno a niveles que pueden producir el RMS. Sin embargo, estas estimaciones del estado del stock estaban

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asociadas a una incertidumbre muy elevada, que podría ser explicada parcialmente por la falta de contraste en la tendencia continuamente decreciente de la biomasa que contiene poca información acerca de la productividad. Basándose en la inferencia de los diversos modelos a partir de los cuatro escenarios finales seleccionados para el asesoramiento científico (caso base, S2, S3 y S5), hay una probabilidad del 54,9 % de que el stock esté sobrepescado y una probabilidad del 51,4% de que se esté produciendo todavía sobrepesca.

KEYWORDS

Yellowfin tuna, stock status, model diagnostics, Pella-Tomlinson,

1. Introduction

The latest stock assessment for the yellowfin tuna (*Thunnus albacares*) was carried out by the International Commission for the Conservation of Atlantic Tunas (ICCAT) in 2016. Four modeling approaches were used to estimate the stock status: (i) a non-equilibrium surplus production model ASPIC (Prager, 2002), (ii) an age-structured production model (ASPM), (iii) the integrated Stock Synthesis model (Methot and Wetzel, 2013) and (iv) a virtual population analysis (VPA). The results from these models indicated that the stock's biomass was probably below sustainable levels that can produce MSY ($B<B_{MSY}$), but not undergoing overfishing ($F < F_{MSY}$) at that time (ICCAT, 2016). Management benchmarks resulting from the median across the modeling approaches were estimated to be B_{2014}/B_{MSY} at 0.95 (0.71-1.36, 10th and 90th percentiles) and F_{2014}/F_{MSY} was 0.77 (0.53-1.05, 10th and 90th percentiles). Despite the status of the yellowfin tuna stock being characterized below B_{MSY}, ICCAT recognized the high uncertainty about the stock status results, with an estimated 45.5% probability of the stock was healthy in 2014 (not overfished and overfishing not occurring), 41.2% chance that the stock was overfished ($B < B_{MSY}$) but not experiencing overfishing ($F > F_{MSY}$), and a 13.3% probability that the stock was both overfished and undergoing overfishing (ICCAT, 2016). In addition, ICCAT also recognized a high uncertainty in the annual trajectories of biomass and fishing mortality, since these were not adjusted for likely changes in selectivity that had occurred in the fishery (ICCAT, 2016).

To assist with the 2019 yellowfin tuna stock assessment, we developed a JABBA model (v1.5 Beta, Winker et al., 2018a), using updated catch and CPUE time series through 2018. JABBA is a Bayesian State Space Surplus Production Model that has been formally included in the ICCAT stock assessment software catalogue (https://github.com/ICCAT/software/wiki/2.8-JABBA). In this document we present the final set of the JABBA model runs considered by the ICCAT Tropical Working Group during the meeting, which include estimates of key model parameters, trends in population abundance and fishing mortality, as well as model diagnostics.

2. Material and Methods

2.1. Fishery data

The ICCAT secretariat estimates catch for many fleets and nations based on the best information available. For this stock assessment, the updated total catch from 1950-2018 were obtained from the analysis carried out after the data preparatory meeting in April 2019 (ICCAT, 2019) (**Figure 1**). Several indices of relative abundance were made available in the form of standardized catch-per-unit-of-effort (CPUE) time series, however, the following CPUE time series were suggested for this assessment:

- A standardized joint index based on the longline CPUE from Japan, USA, Brazil, Korea, and Chinese-Taipei from region 1 (Joint_LL_R1 – equatorial area) and region 2 (Joint_LL_R2 - tropical area) (see details in Hoyle et al., 2019; SCRS/2019/081), covering a time period from 1979 to 2018 (**Figure 2**);

- An abundance index of juvenile based on the echosound data collected from the buoys (see details in Santiago et al., 2019; SCRS/2019/075), covering a time period from 2010 to 2017 (**Figure 2**) and;

- A standardized index based on the EU purse seine fleet that operates over yellowfin tuna free schools (EUPSFS) (see details in Guéry et al., 2019; SCRS/2019/066), covering a time period from 1993 to 2018 (**Figure 2**).

For the final JABBA Stock Assessment scenarios, only the joint longline indices (Joint_LL_R01 and Joint_LL_R02) and the EU purse seine index (EUPSFS) were used.

2.2. JABBA stock assessment model fitting procedures

This stock assessment uses the most updated version (v1.5beta) of JABBA, which can be found online at: www.github.com/henning-winker/JABBAbeta. JABBA's inbuilt options include: (1) automatic fitting of multiple CPUE time series and associated standard errors; (2) estimating or fixing the process variance, (3) optional estimation of additional observation variance for individual or grouped CPUE time series, and (4) specifying a Fox, Schaefer or Pella-Tomlinson production function by setting the inflection point B_{MSY}/K and converting this ratio into shape a parameter m.

For the unfished equilibrium biomass K, we assumed a vaguely informative lognormal prior with a mean of 1,000,000 mt and a large CV of 200%. Initial depletion lognormal prior ($\varphi = B_{1950}/K$; for details see Winker et al., 2018a) was inputted with mean = 1 and CV of 10%. All catchability parameters were formulated as uninformative uniform priors. The observation variance and process error variance of $log(B_y)$ were estimated using uninformative inverse-gamma priors with both scaling parameters setting at 0.001 (for details see Winker et al., 2018a). For r priors and input values of B_{MSY}/K we considered the following three parameterizations:

1. **SS3 2016 *r* prior**: The prior mean r and the corresponding shape parameter m were calculated using the reference point estimates for F_{MSY}, MSY of B_0 (unfished biomass Age-1+) from the 2016 Stock Synthesis base-case models for Atlantic yellowfin tuna (ICCAT, 2017). We calculated $B_{MSY} = MSY/F_{MSY}$ and then used equation (2) and (5) in Winker et al. 2019 (SCRS/2019/103) to calculate the shape m as function of B_{MSY}/B_0 and r as function of F_{MSY} and m, respectively. Assuming a CV of 20%, we formulated the resulting r prior as $log(r) \sim N(log(0.2757), 0.2)$ with a fixed input value of B_{MSY}/K = 0.3412;

2. **SS3 2019 *r* prior**: Assuming the same method described above, but applied to the 2019 Stock Synthesis base-case model estimates, which resulted in a r prior of $log(r) \sim N(log(0.1701), 0.1728)$ with a fixed input value of B_{MSY}/K = 0.3420.

3. **FishLife *r* prior**: We applied the approach developed by Winker et al. (2019; SCRS/2019/103) to translate the ratios of MSY to the exploitable biomass at (EB_{MSY}) and EB_{MSY} to the unfished exploitable biomass (EB_0) derived from an age-structured equilibrium model (ASEM) into the surplus production parameters r and m. The input life history parameter distributions for the ASEM were estimated using the FishLife package version 2 (Thorson, in press) as described in Winker et al. (2018b). Based on Monte-Carlo simulations to randomly draw from the life history parameter distributions, the initial r prior was formulated as $log(r) \sim N(log(0.34), 0.2)$ with a fixed input value of B_{MSY}/K = 0.39 (see Winker et al. 2018b for details).

During the stock assessment meeting for the Atlantic yellowfin tuna, the ICCAT Tropical Working Group considered various JABBA model runs (**Table 1**). Based on the discussions on all sensitivity analysis including the initial submitted runs (Run 1-4 in **Table 1**), the following six specific scenarios were considered as a final set of JABBA runs by the Working Group:

- **Base case**: including only Joint_LL_R2 CPUE series with SS3 2019 prior;
- **S1:** including only Joint_LL_R2 CPUE series with SS3 2016 prior;
- **S2:** including only Joint_LL_R2 CPUE series with FishLife prior;
- **S3**: including Joint_LL_R1, Joint_LL_R2 and EUPSFS CPUE series with SS3 2019 prior;
- **S4:** including Joint_LL_R1, Joint_LL_R2 and EUPSFS CPUE with SS3 2016 prior;
- **S5:** including Joint_LL_R1, Joint_LL_R2 and EUPSFS CPUE with FishLife prior.

The diagnostics included the JABBA-residual plot (Winker et al. 2018a), the Root-Mean-Squared-Error (RMSE) fit to the loess smoother of all residuals CPUE indices combined and the runs test to detect non-randomness in CPUE residuals (Carvalho et al. 2017). The runs test diagnostic was applied to residuals of the CPUE fit on log-scale using the function *runs.test* in the R package *tseries* (Trapletti, 2011), considering the 2-sided p-value of the Wald-Wolfowitz runs test. The runs test results were visualized using a specifically designed plot that illustrates which time series passed or failed the runs test and highlights individual time-series data points fall outside the three-sigma limits (e.g. Anhøj and Olesen 2014). Each diagnostic approach was applied in order to quantitatively evaluate the randomness of the time series of CPUE residuals by fleet (except RMSE).

To verify systematic bias in the stock status estimates, we also performed a retrospective analysis for each scenario, by removing one year of data at a time sequentially (n = 8) and predicting the stock status in the form of B/B_{MSY} and F/F_{MSY} trajectories one year ahead. 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, four MCMC chains were used. The models were run for 50,000 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.

3. Results and Discussion

For all scenarios the visual inspection of trace plots (results not shown here) of the key model parameters showed good mixing of the four chains (*i.e.*, moving around the parameter space). This is also an indicative of convergence of the MCMC chains and that the posterior distribution of the model parameters was adequately sampled with the MCMC simulations. JABBA residual plots showed that distributions of residuals were similar between base case and scenarios S1 and S2 with RMSE values around 9%, which indicates a fairly good fit to CPUE data (**Figure 3**). Not unexpectedly, the inclusion of an additional CPUE index in the form of the EUPSFS CPUE (scenarios S3, S4 and S5) caused some moderate data conflicts, which also resulted in reduced goodness-of-fit statistics (RMSE ~ 16%); **Figure 3**). Overall, the fits remained reasonably good (RMSE < 30%), albeit associated with a notable negative residual pattern over the early part of the time series between 1979 and 1992.

Figure 4 shows the results of the residuals runs test for each CPUE fit by year and scenario. Green panels indicate no evidence of lack of randomness of time-series residuals ($p > 0.05$). The inner shaded area shows 3-sigma limits (Anhøj and Olesen, 2014) around the overall mean and red circles identify a specific year with residuals greater than this threshold limit. In general, the scenarios base on a single CPUE series (Base Case, S1 and S2) had passed the runs test diagnostic and models seems to be adequately fitted with no major problems of model misspecifications and/or apparent data conflicts. For scenarios with multiple CPUE series (S3, S4 and S5), the runs test results suggested a lack of randomness for the Joint_LL_R1 and Joint_LL_R2 CPUEs series.

The predicted CPUE indices from the models fits were compared to the observed CPUE for each scenario (**Figure 5**). The model fits for yellowfin tuna CPUEs indicated that there was a slightly lack of fit for the scenarios with multiple indices. In general, this pattern mostly pertained to the early years of the Joint_LL_R1 and EUPSFS CPUE indices, while the observed CPUE values from the Joint_LL_R2 has presented a reasonably good fit. Plots of process error deviates by year indicated that models presented a similar stochastic pattern with a pronounced negative trend after 2008 until the final of the time series when observed the central tendency (e.g. median signal) (**Figure 6**). However, the 95% Bayesian credibility interval (CIs) always included zero, which might be considered a statistical evidence for a non-significant effect of this trend. Although, the signal cannot be neglected, assuming that the process error commonly describes natural variations in stock biomass, natural mortality, growth, recruitment and maturation this behavior could be considered as a first signal of the negative trends in the Atlantic Yellowfin tuna stock (Punt, 2003; Winker et al, 2018).

Posterior densities along with prior densities are shown in **Figures 7-12** and 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 0.156 and 0.290 among scenarios. When comparing posterior and prior distributions for r, all scenarios presented a good agreement and a broad overlap between the density distributions (except for scenarios S1, S2 and S5), with a slight dislocation to the left of the mean of posterior distributions in relation to the priors. The median of marginal posterior for K varied between 1,417,812 metric tons (scenario S2) and 2,231,839 metric tons (scenario S4) **(Table 1**). It was also noted that posterior distributions for K showed the same pattern among all scenarios, with posterior dislocated to the right in comparison to their priors, which indicates that the input data was very informative about K for all fitted models (**Figures 7-12)**. The marginal posteriors for initial depletion (φ) were similar for all scenarios and posterior densities for all scenarios produced a good agreement with the prior distributions (**Figures 7-12**).

Estimates of MSY showed little variation across model runs, ranging from 130,860 to 143,680 metric tons among all six scenarios (**Table 1**). The marginal posterior median for B_{MSY} varied between 520,569 metric tons (S4) and 763,204 metric tons (S3) (**Figures 7-12**). The median F_{MSY} estimates were very similar (varying between 0.178 and 0.279) among scenarios (**Table 1**). All scenarios showed the typical characteristics of a one-way downhill trip (Hilborn 1979), signified by a continuous decline in biomass over the time series (**Figure 13**). The six scenarios produced very most similar trajectories in terms of biomass depletion (*B/K*), with all estimates for 2018 falling between 30% and 40% of the unfished biomass (**Figure 13**). With the exception of the more pessimistic scenario S2, B/B_{MSY} estimates for the final year 2018 were generally close to *MSY*. The F/F_{MSY} trajectories showed an increasing trend from the beginning of the time series until 1990, followed by a somewhat stable trend until 2000 and a decreasing trend until 2008. After 2010, F/F_{MSY} started to increase substantially again. The F/F_{MSY} trajectories for the basecase and S2 exceeded sustainability levels after 2014 ($F/F_{\mathrm{MSY}} > 1$), and remained above F_{MSY} through 2018, whereas fishing mortality estimates from the other four scenarios fell below F_{MSY} in 2018 (**Figure 13**). Most contrast among model scenarios was apparent among the scales of absolute biomass and fishing mortality estimates (**Figure 13**).

Retrospectives analyses conducted over eight sequential years for each scenario are shown in **Figures 14-19.** Results showed slight to moderate retrospective patterns. For scenarios S2, S4 and S5, the B/B_{MSY} trajectories fell slightly above the reference case, while the F/F_{MSY} trajectories showed a stronger systematic retrospective pattern with an opposite trend with most values falling below of the reference case, especially after mid-1980's (**Figures 14-19**). In general, the base case and scenario S2 showed only a slight retrospective pattern and thus performed superior in comparison to the other scenarios for this model diagnostic.

The Kobe phase plots portrait similar exploitation histories for all six scenarios, with the trajectories moving from underexploited phase in direction to overexploited phase in recent years (**Figure 20**). The resulting stock status posteriors for 2018 were characterized by a high uncertainty for almost all scenarios with probabilities approximately equally (around 50%) divided between underexploited and overexploited phase (**Figure 20)** .Based on multi-model inference from the select final scenarios (Base Case, S2, S3 and S5), there is a 54.9% probability that the stock remains overfished and a 51.4% probability that overfishing is still occurring (**Figure 21**). The high uncertainty about the stock status may be partially explained by the lack of contrast in the "one-way downhill trip" of the continuously declining biomass, which typically contains limited information about productivity (Hilborn 1979). This is associated with a substantial risk that stock is overfished and is undergoing overfishing until the ongoing decline can be reversed or at least halted.

References

Anhøj, J., Olesen, A.V., 2014. Run charts revisited: A simulation study of run chart rules for detection of non-random variation in health care processes. PLoS One 9, 1–13.

Anon. 2009. Report of the 2008 ICCAT yellowfin and skipjack stock assessments meeting (Florianópolis, Brazil – July 21 to 29, 2008). Collect. Vol. Sci. Pap. ICCAT, 64(3): 1634-927.

Anon. 2017. Report of the 2016 ICCAT yellowfin tuna stock assessment meeting (San Sebastian, Spain – June 27 to July 1, 2016). Collect. Vol. Sci. Pap. ICCAT, 64(3): 1634-927.

Carvalho, F., Punt, A. E., Chang, Y.-J., Maunder, M. N., and Piner, K. R. 2017. Can diagnostic tests help identify model misspecification in integrated stock assessments? Fish. Res., 192:28–40.

Hilborn, R., 1979. Comparison of fisheries control systems that utilize catch and effort data. J. Fish. Board Canada 36: 1477–1489.

Hoyle, S. D., Lauretta, M., Lee, M. K., Matsumoto, T., Sant'Ana, R., Yokoi, H., Su, N. 2019. Collaborative study of yellowfin tuna cpue from multiple Atlantic Ocean longline fleets in 2019. ICCAT – Collect. Vol. Sci. Pap. ICCAT, 76(6): 241-293 (2019).

ICCAT. 2016. Report of the 2016 ICCAT yellowfin tuna stock assessment meeting. 108 pp.

ICCAT. 2019. Report of the 2019 ICCAT yellowfin tuna data preparatory meeting. 51pp.

Methot, R.D., Wetzel, C.R., 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142, 86–99.

Plummer, M., 2003. JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling. In: 3rd International Workshop on Distributed Statistical Computing (DSC 2003). Vienna, Austria.

Prager, M.H., 2002. Comparison of logistic and generalized surplus-production models applied to swordfish, *Xiphias gladius*, in the north Atlantic Ocean. Fish. Res. 58, 41–57.

Santiago, J., Uranga, J., Quincoces, I., Orue, B., Grande, M., Murua, H., Merino, G., Boyra, G. 2019. A novel index of abundance of juvenile yellowfin tuna in the Atlantic Ocean derived from echosounder buoys. ICCAT – SCRS/2019/075 (*In press*).

Thorson, J.T., (in press). Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. Fish Fish.

Trapletti, A., 2011. tseries: Time series analysis and computational finance. Rpackage version 0. 10-25. http://CRAN.R-project.org/package=tseries.

Winker, H., Carvalho, F. and Kapur, M. 2018a. JABBA: Just Another Bayesian Biomass Assessment. Fish. Res. 204: 275–288.

Winker, H., Kerwath, S., de Bryun, P. 2018b. Developing surplus production model priors from a multivariate life history prediction model for IOTC billfish assessments with limited biological information. IOTC–2018–WPB16–14_Rev1.

Winker H., Mourato B, Chang Y-J 2019. Unifying parameterizations between age-structured and surplus production models: an application to Atlantic white marlin (*Kajika albida*) with simulation testing. ICCAT - SCRS/2019/103.

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 yellowfin tuna.

		Base Case			**S1**	
Estimates	Median	2.50%	97.50%	Median	2.50%	97.50%
K	2164692	1544557	3823105	1711766	1138849	3436580
r	0.156	0.114	0.216	0.221	0.154	0.313
y (*psi*)	0.992	0.819	1.195	0.993	0.816	1.195
σ_{proc}	0.084	0.045	0.134	0.100	0.063	0.152
F_{MSY}	0.180	0.131	0.249	0.256	0.178	0.362
B_{MSY}	740243	528180	1307357	583942	388500	1172335
MSY	130860	108611	230106	143680	117832	298423
B_{1950}/K	0.988	0.762	1.244	0.987	0.743	1.261
B_{2018}/K	0.323	0.195	0.561	0.352	0.183	0.614
$B_{2018}/B_{\mathrm{MSY}}$	0.944	0.570	1.641	1.031	0.536	1.801
$F_{2018}/F_{\mathrm{MSY}}$	1.066	0.361	1.913	0.889	0.261	1.916
		S2			**S3**	
	Median	2.50%	97.50%	Median	2.50%	97.50%
K	1417812	1026690	2092314	2231839	1573872	4132331
r	0.279	0.194	0.388	0.161	0.117	0.219
y (*psi*)	0.993	0.817	1.197	0.994	0.824	1.196
σ_{proc}	0.100	0.063	0.152	0.077	0.055	0.118
F_{MSY}	0.248	0.172	0.344	0.186	0.135	0.252
B_{MSY}	553055	400488	816163	763204	538204	1413101
MSY	134864	116201	179515	139209	111967	247952
B_{1950}/K	0.990	0.747	1.270	0.992	0.775	1.244
B_{2018}/K	0.305	0.188	0.488	0.390	0.235	0.626
$B_{2018}/B_{\mathrm{MSY}}$	0.781	0.483	1.251	1.140	0.688	1.831
$F_{2018}/F_{\mathrm{MSY}}$	1.258	0.604	2.120	0.834	0.305	1.562
		S4			**S5**	
	Median	2.50%	97.50%	Median	2.50%	97.50%
K	1525995	1083585	2624933	1418202	994702	2559768
r	0.241	0.167	0.333	0.290	0.200	0.408
y (*psi*)	0.995	0.820	1.195	0.997	0.824	1.199
σ_{proc}	0.095	0.063	0.141	0.095	0.063	0.141
F_{MSY}	0.279	0.193	0.386	0.257	0.177	0.362
B_{MSY}	520569	369648	895454	553208	388010	998506
MSY	141320	119515	238006	140278	119530	226154
B_{1950}/K	0.990	0.760	1.262	0.994	0.757	1.265
B_{2018}/K	0.368	0.222	0.609	0.381	0.237	0.603
$B_{2018}/B_{\mathrm{MSY}}$	1.078	0.651	1.784	0.977	0.608	1.547
$F_{2018}/F_{\mathrm{MSY}}$	0.869	0.321	1.567	0.964	0.396	1.670

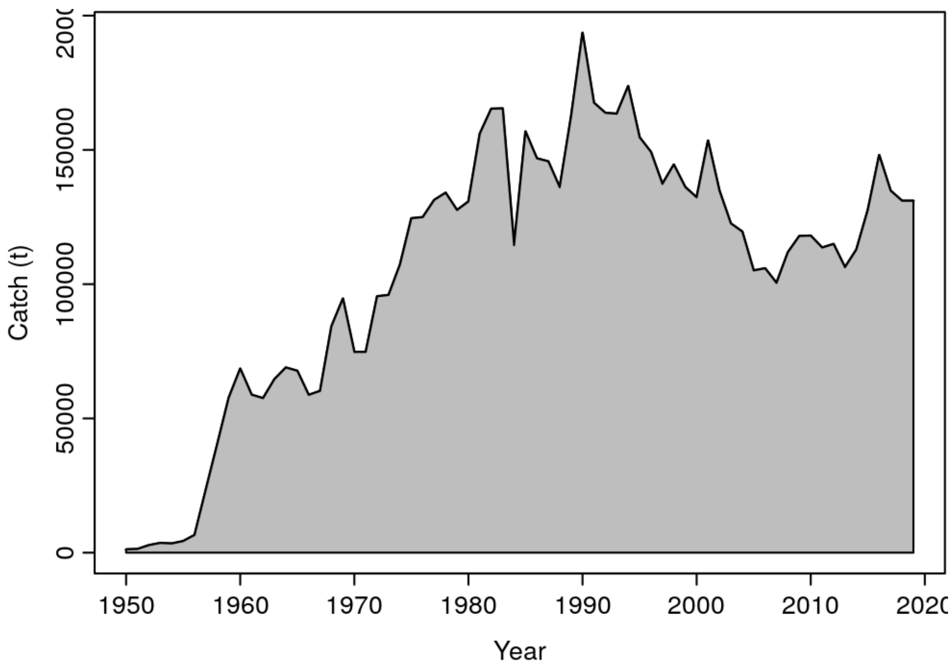

Figure 1. Time-series of catch in metric tons (t) for the yellowfin tuna in the Atlantic Ocean.

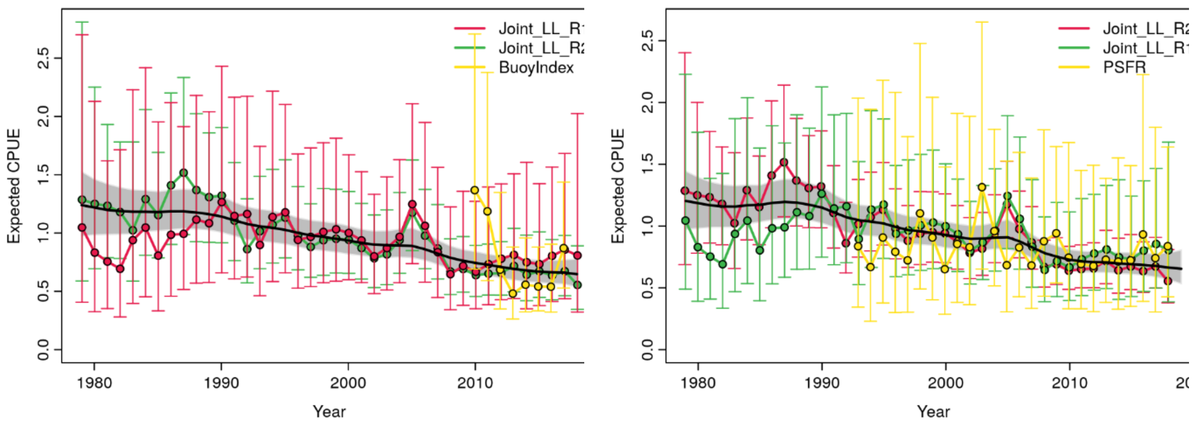

Figure 2. Time-series of three standardized CPUE series for yellowfin tuna in the Atlantic Ocean. The solid black line and associated grey shaded area represents the state-space CPUE averaging tool implemented in JABBA.

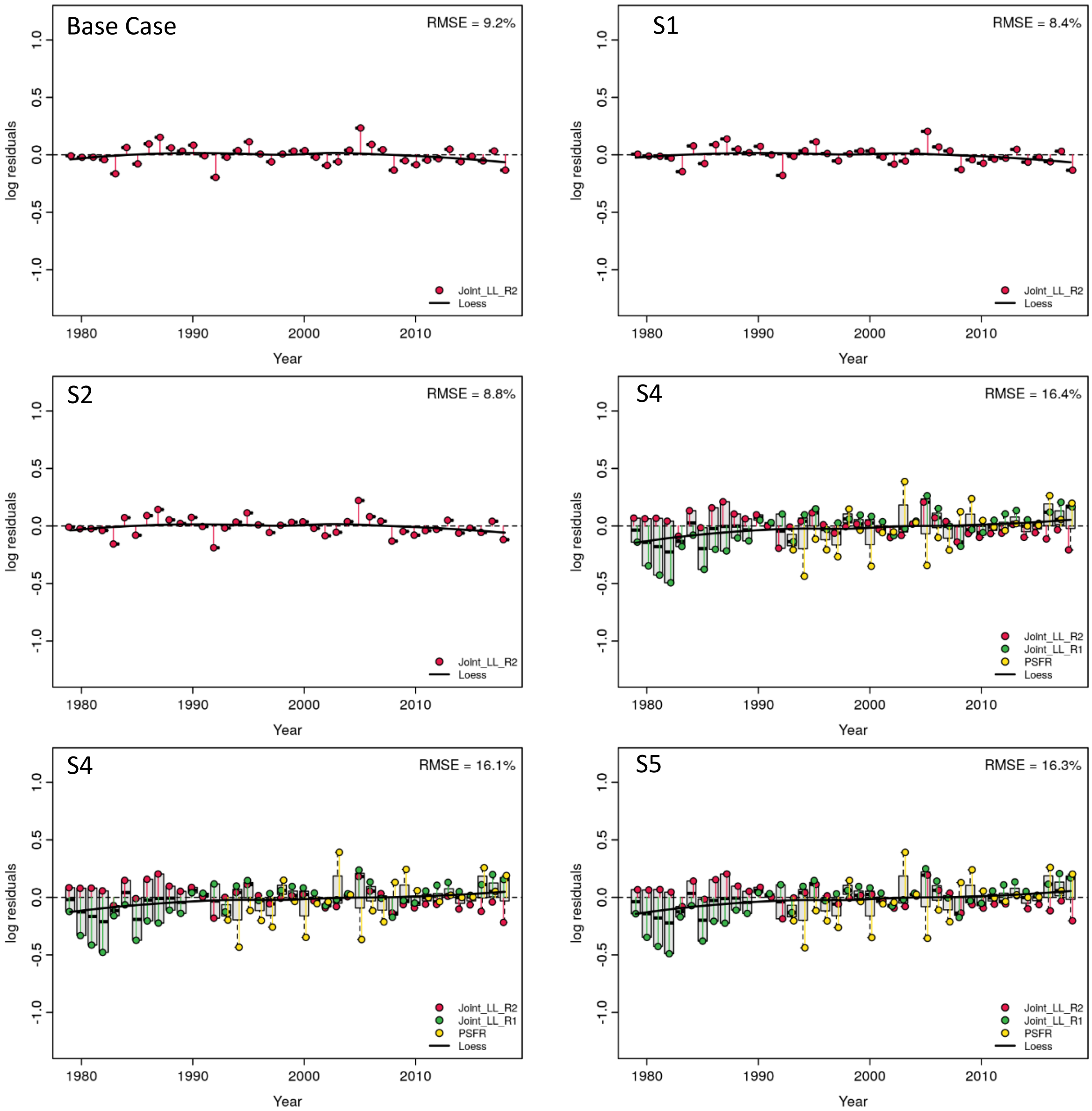

Figure 3. JABBA residual diagnostic plots for alternative sets of CPUE indices examined for each scenario for the Atlantic yellowfin tuna. Boxplots indicate the median and quantiles of all residuals available for any given year, and solid black lines indicate a loess smoother through all residuals.

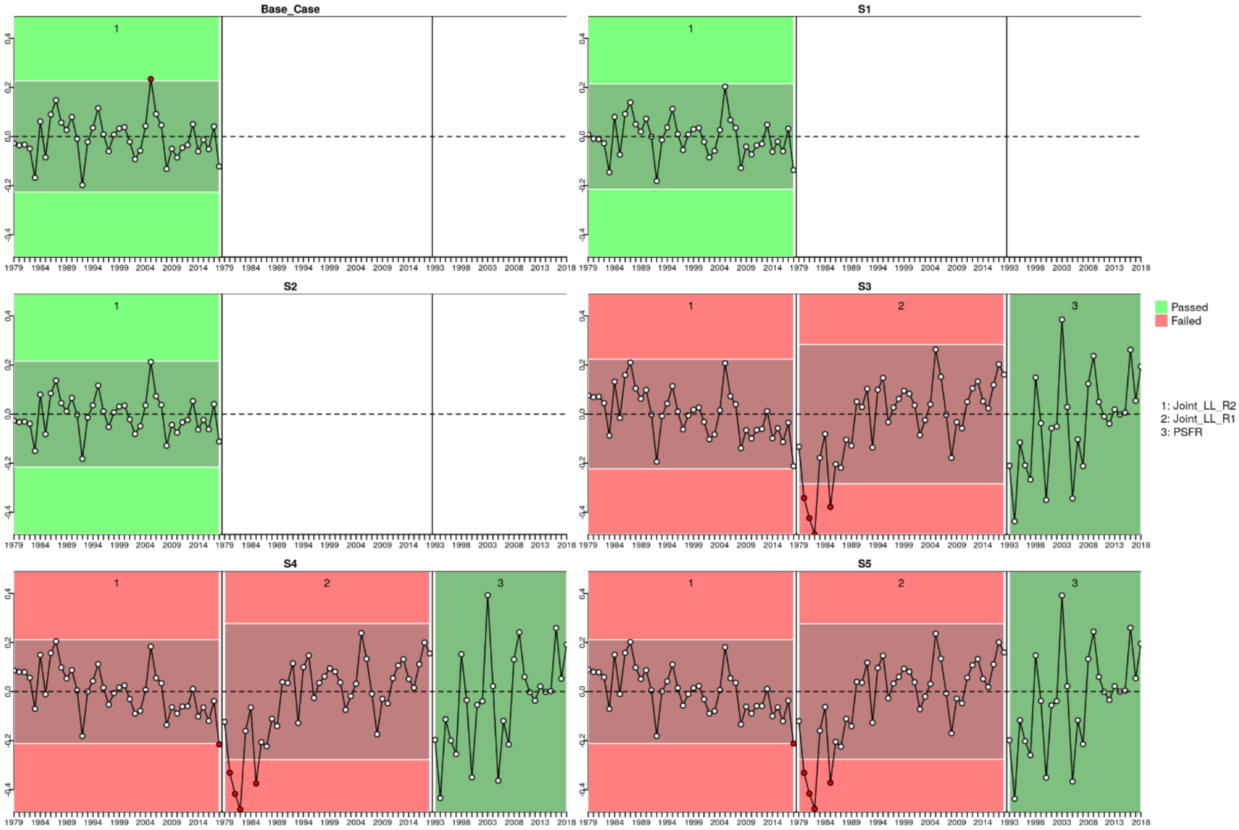

Figure 4. Runs tests to quantitatively evaluate the randomness of the time series of CPUE residuals by fleet for each scenario. Green panels indicate no evidence of lack of randomness of time-series residuals (p>0.05) while red panels should indicate the opposite (not shown here). The inner shaded area shows three standard errors from the overall mean and red circles identify a specific year with residuals greater than this threshold value (3x sigma rule).

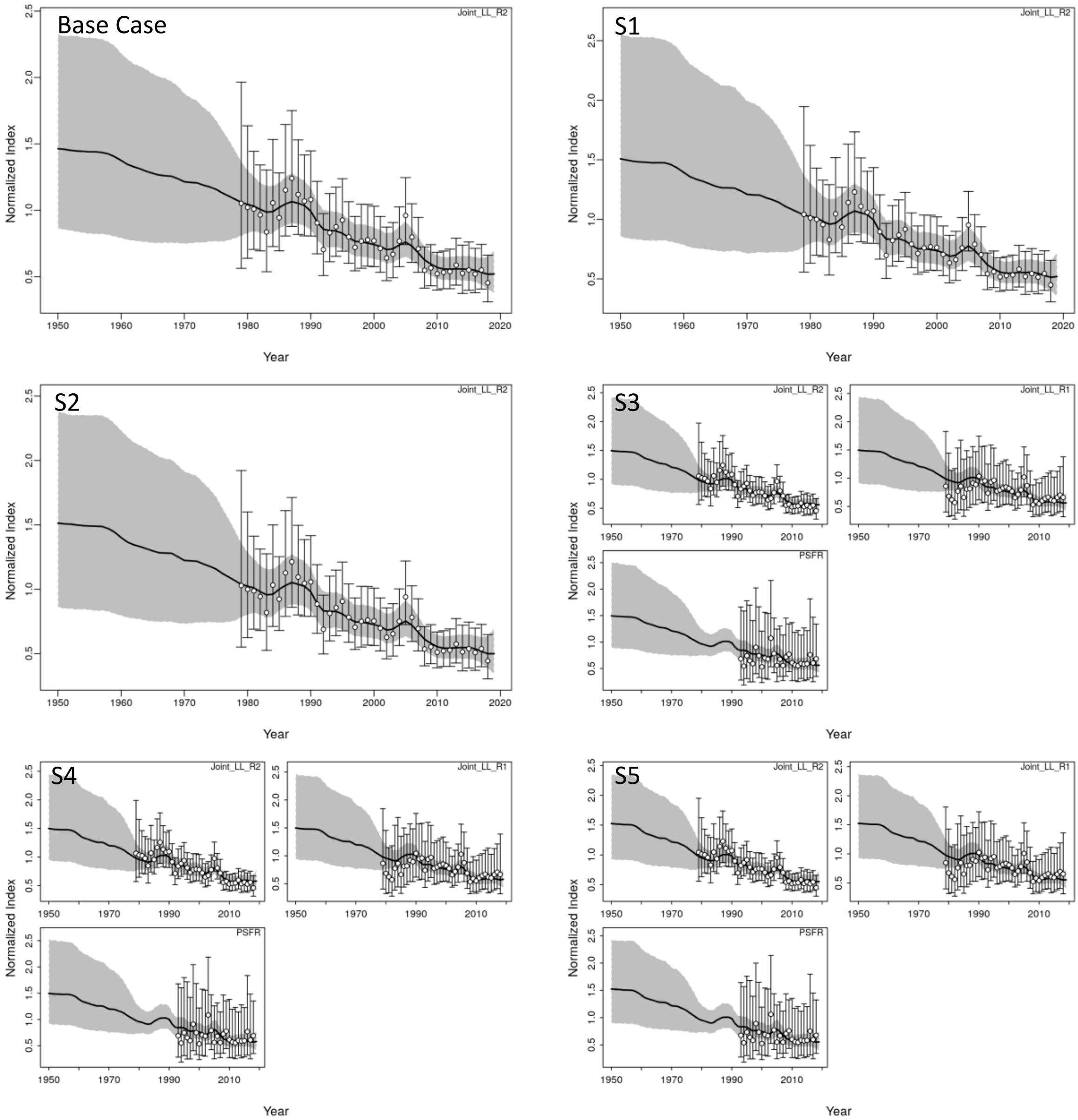

Figure 5. Time-series of observed (circle and SE error bars) and predicted (solid line) CPUE of yellowfin tuna in the Atlantic Ocean for the Bayesian state-space surplus production model JABBA for all scenarios. Shaded grey area indicates 95% credibility intervals.

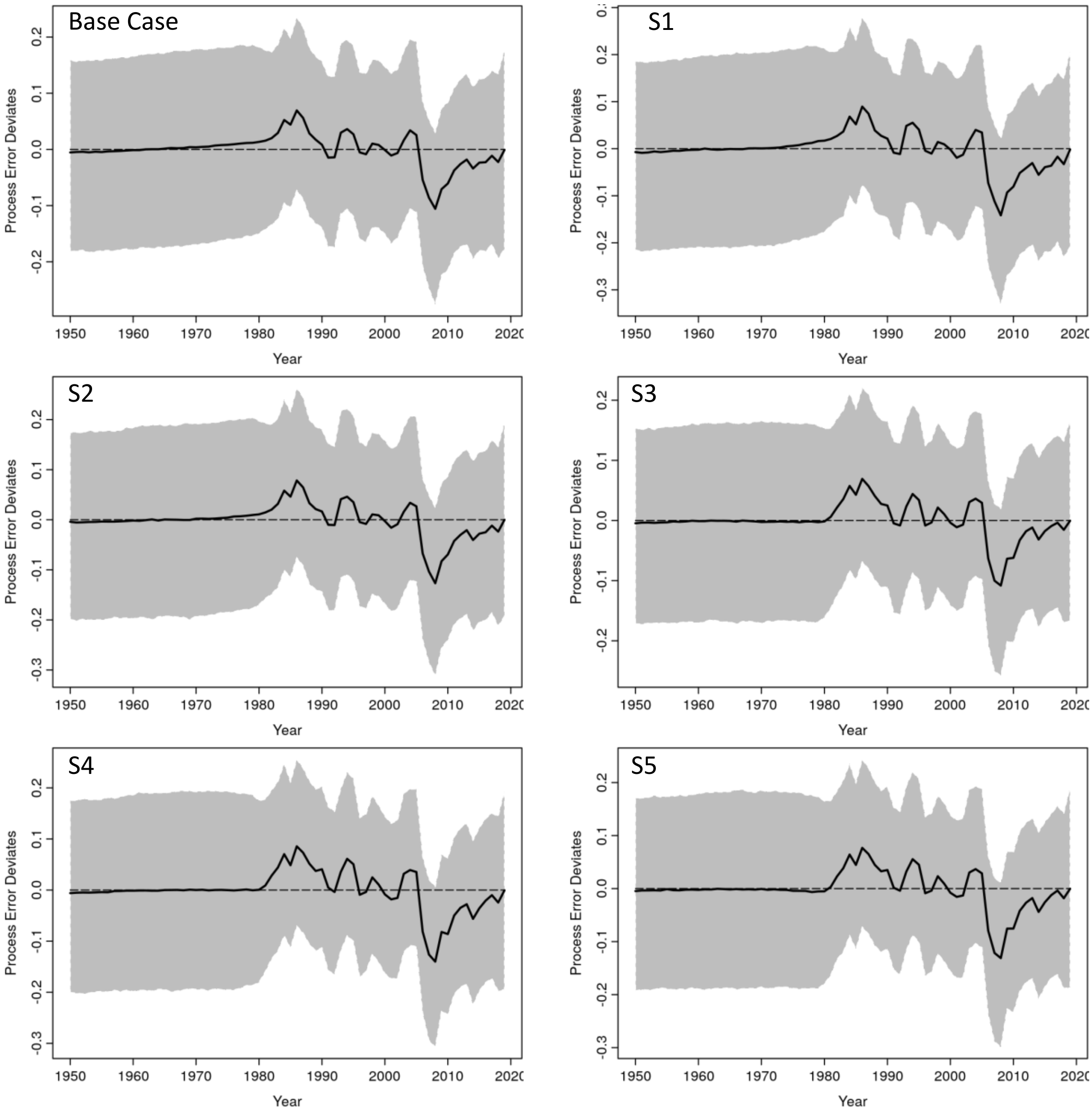

Figure 6. Process error deviates between the deterministic expectation and the stochastic realizations of the predicted log biomass (median: solid line) for yellowfin tuna in the Atlantic Ocean using the Bayesian state-space surplus production model JABBA, shown for each scenario. Shaded grey area indicates 95% credibility intervals.

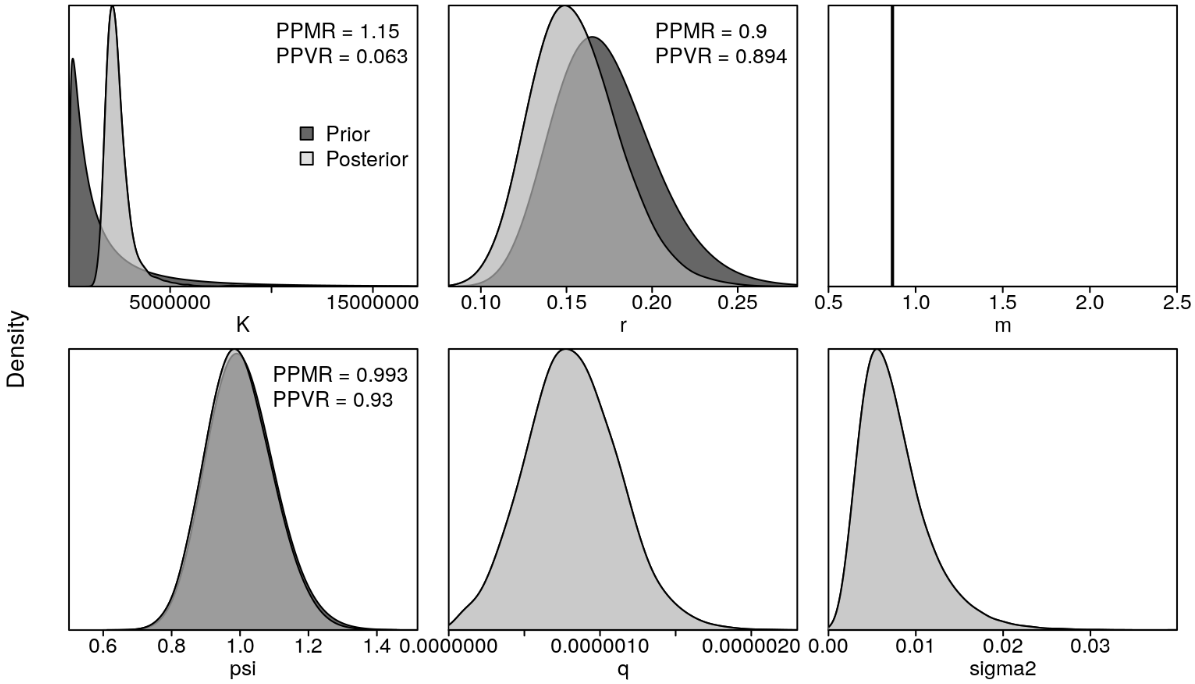

Figure 7. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (Base Case scenario) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior - Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

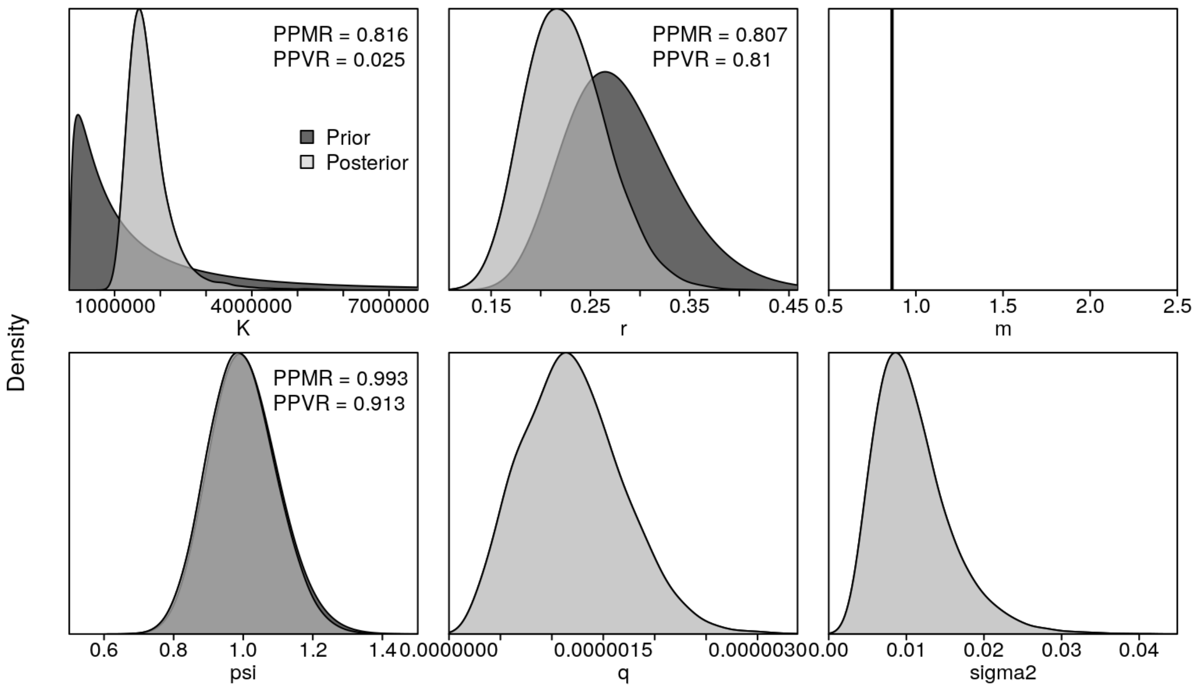

Figure 8. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S1) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior -Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

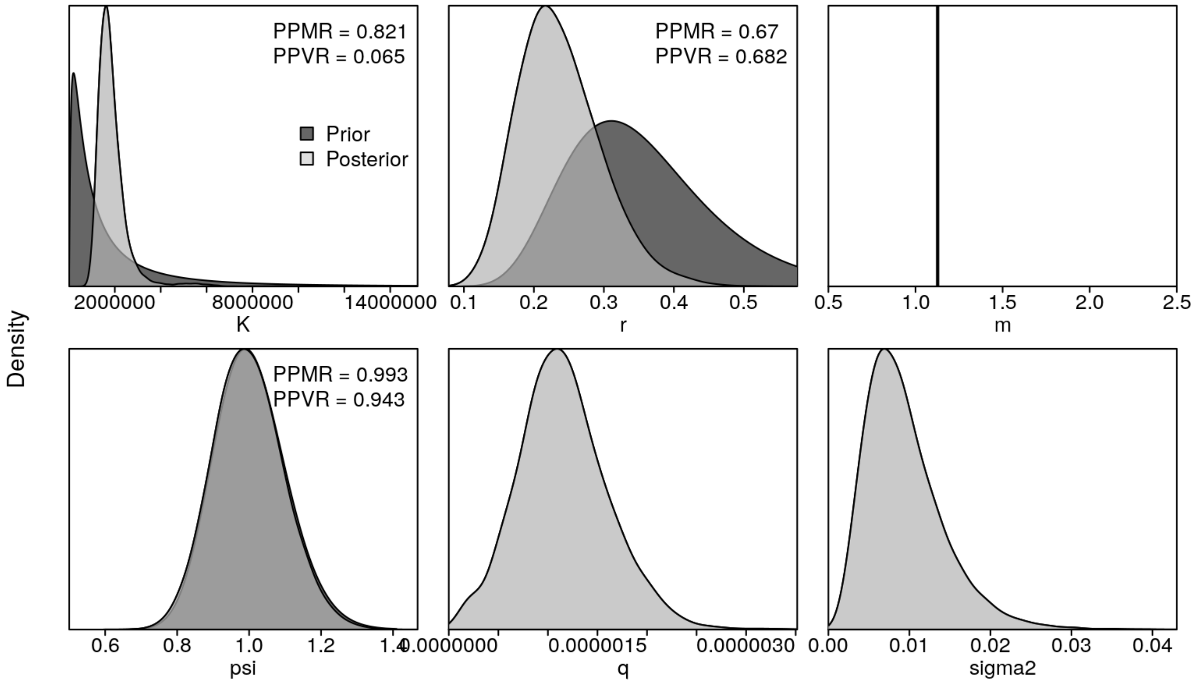

Figure 9. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S2) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior -Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

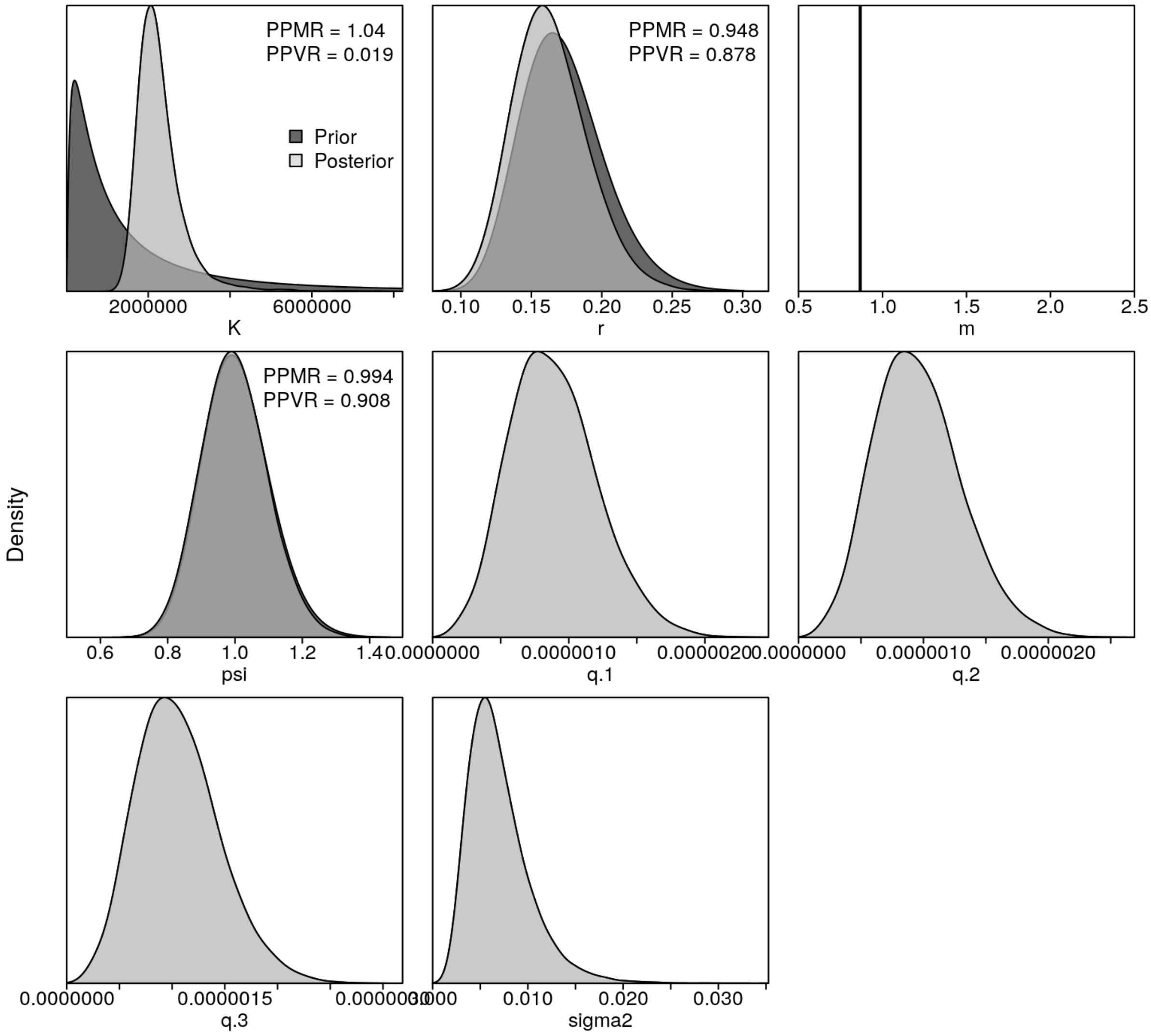

Figure 10. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S3) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior -Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

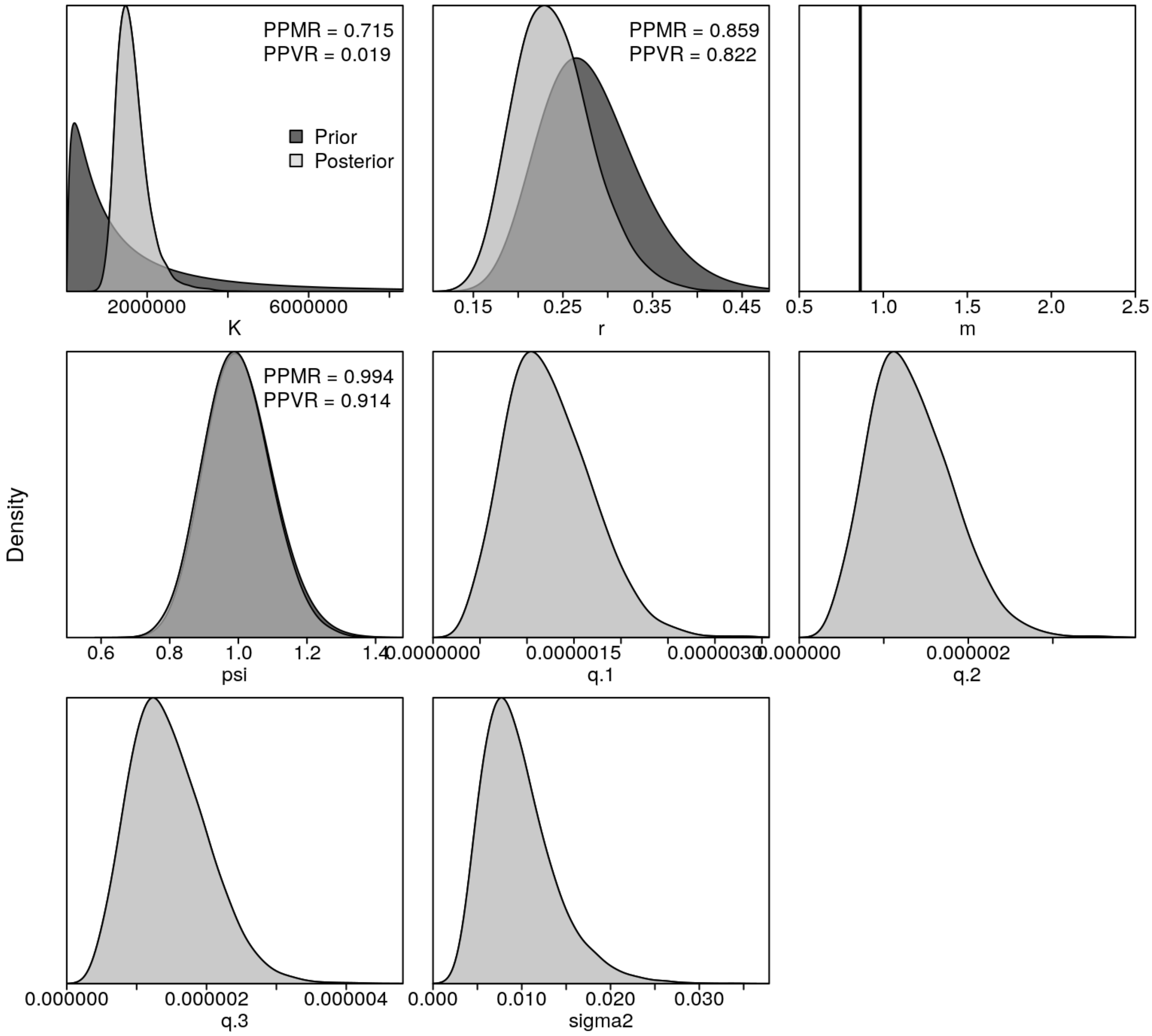

Figure 11. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S4) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior -Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

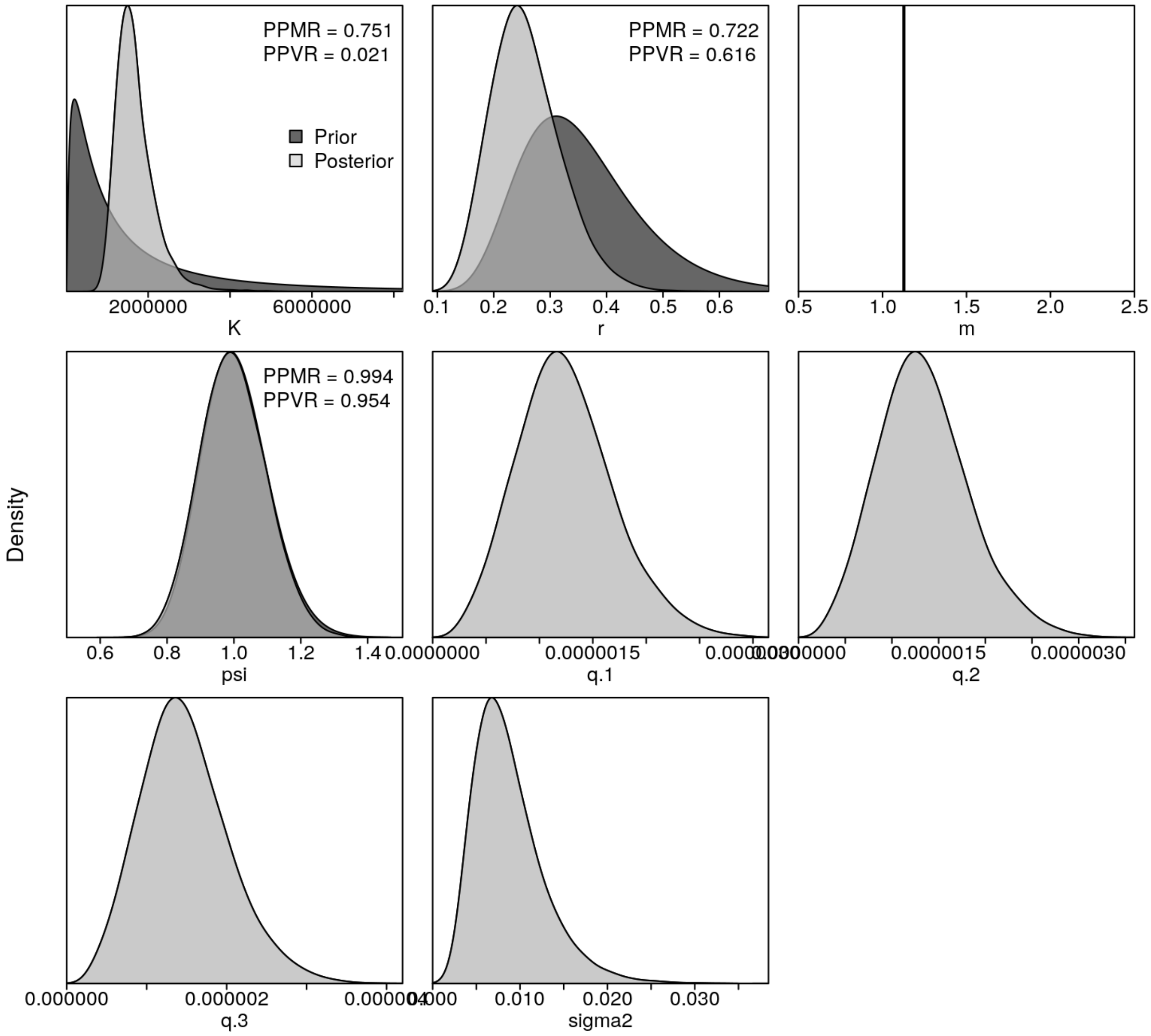

Figure 12. Prior and posterior distributions of various model and management parameters for the Bayesian state-space surplus production model (scenario S5) for yellowfin tuna in the Atlantic Ocean. PPMR: Posterior -Prior Mean Ratio; PPVR: Posterior-Prior Variance Ratio.

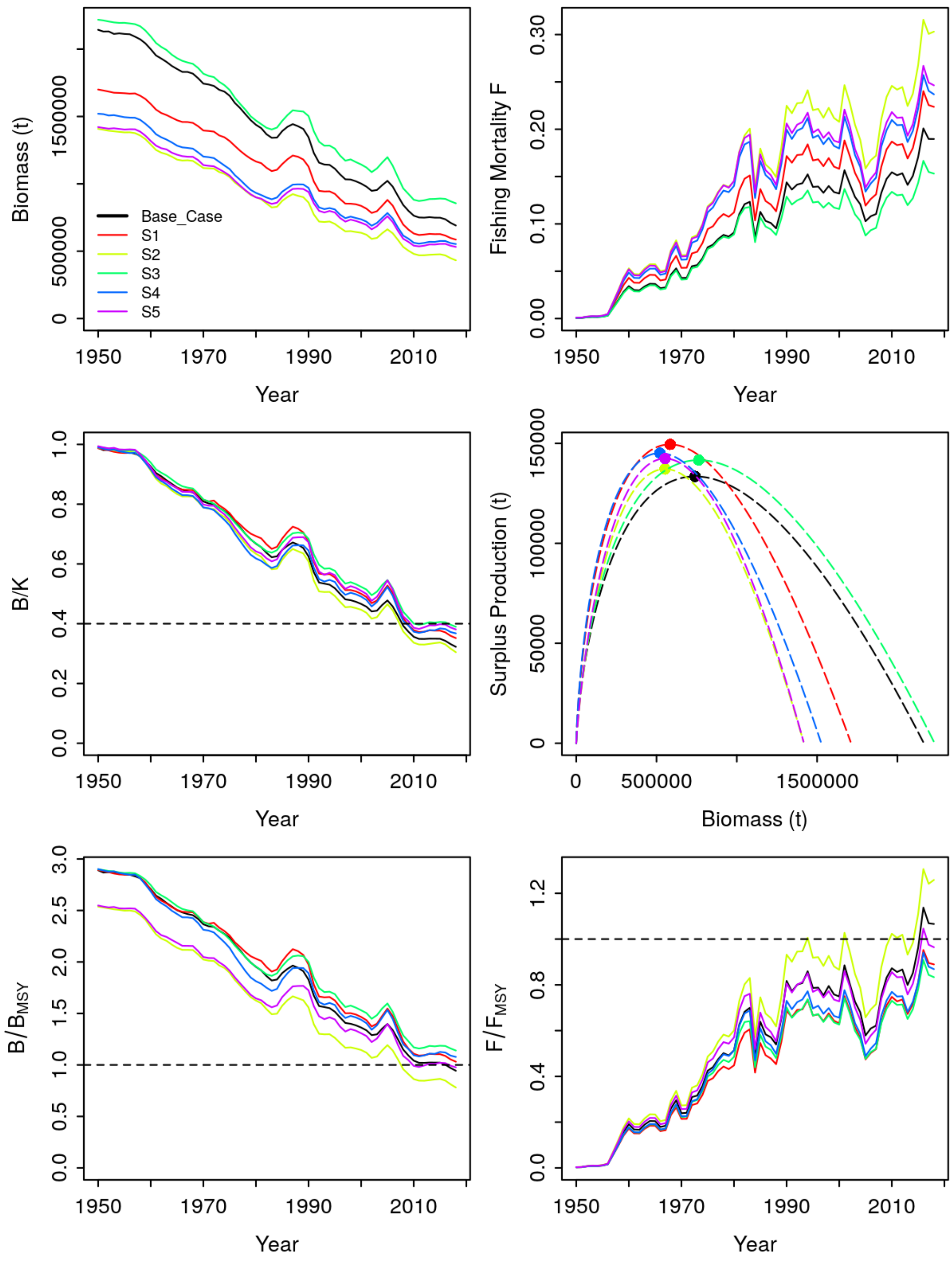

Figure 13. Trends in biomass and fishing mortality (upper panels), biomass relative to *K* (*B/K*) and surplus production curve (middle panels) and biomass relative to B_{MSY} (B/B_{MSY}) and fishing mortality relative to F_{MSY} (F/F_{MSY}) (bottom panels) for each scenario from the Bayesian state-space surplus production model fits to Atlantic yellowfin tuna.

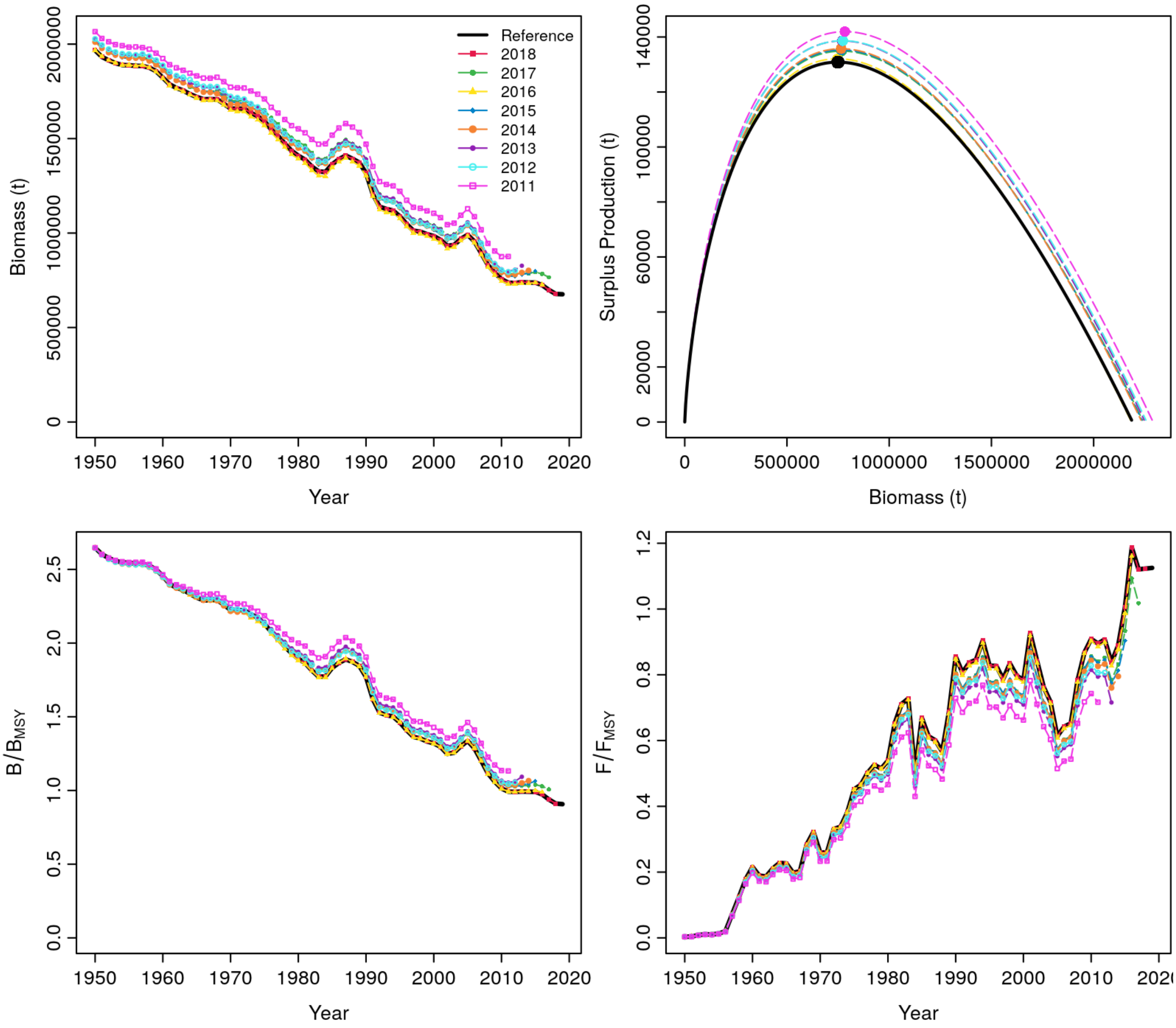

Figure 14. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (base case). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

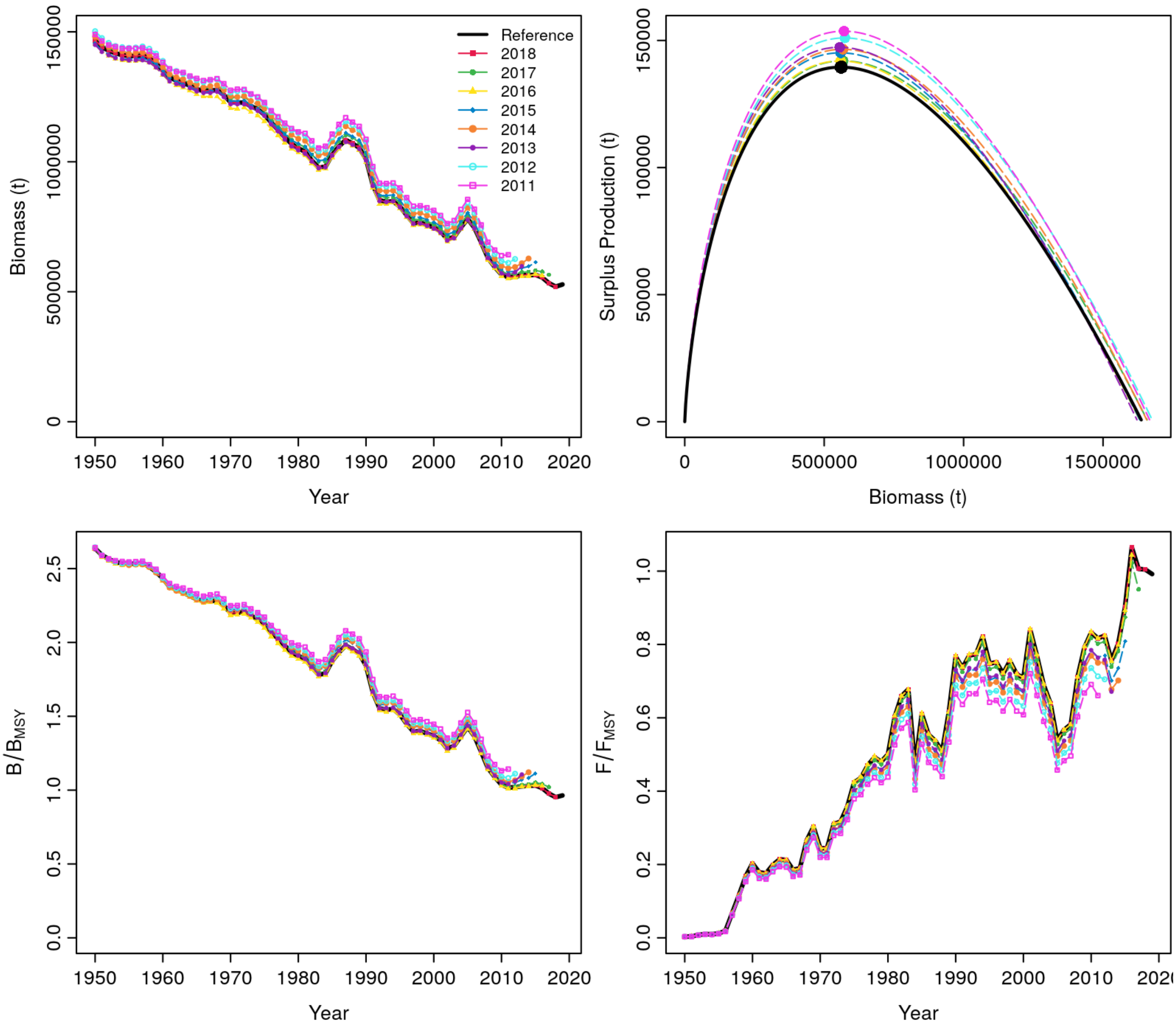

Figure 15. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (Scenario S1). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

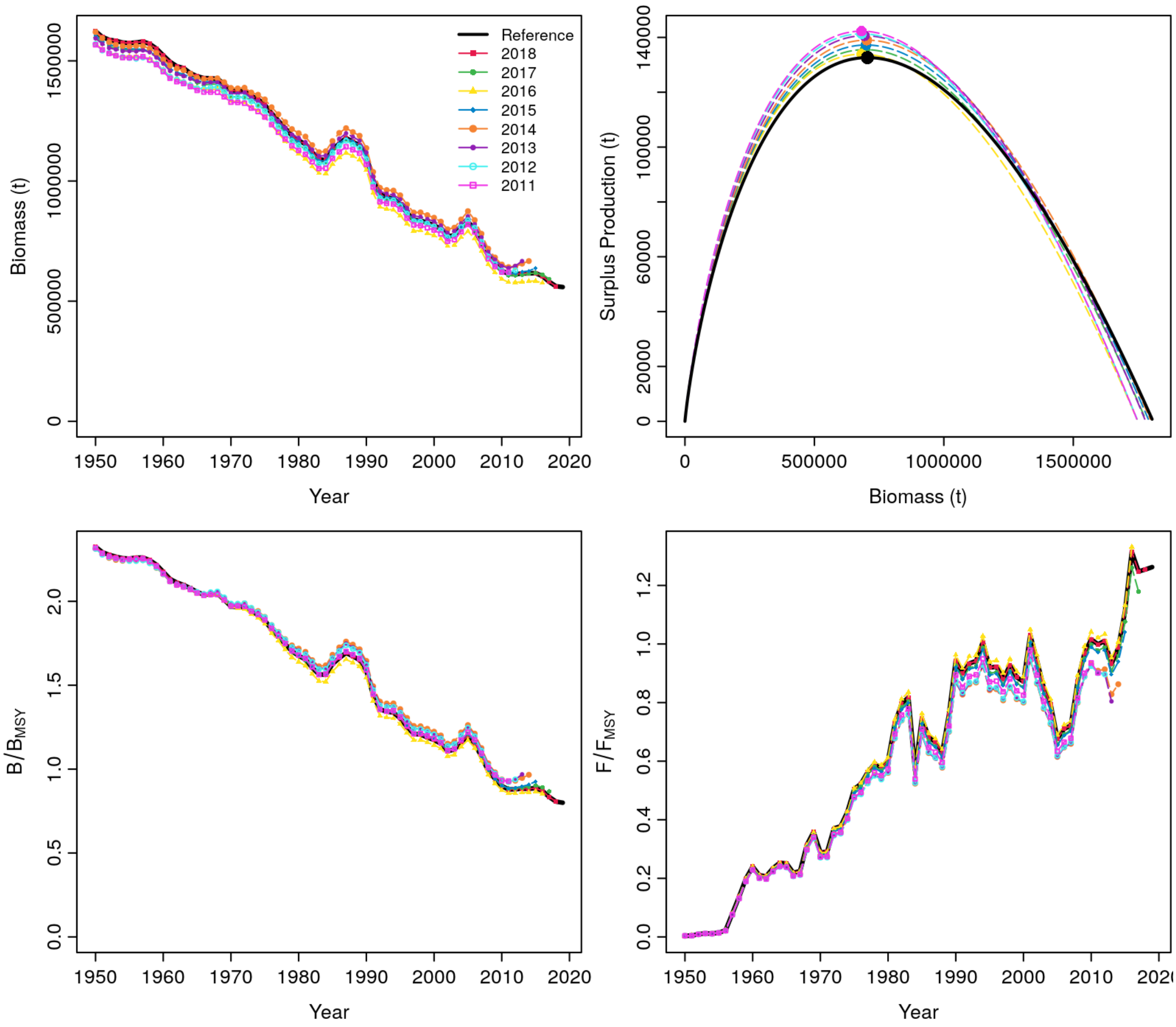

Figure 16. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (Scenario S2). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

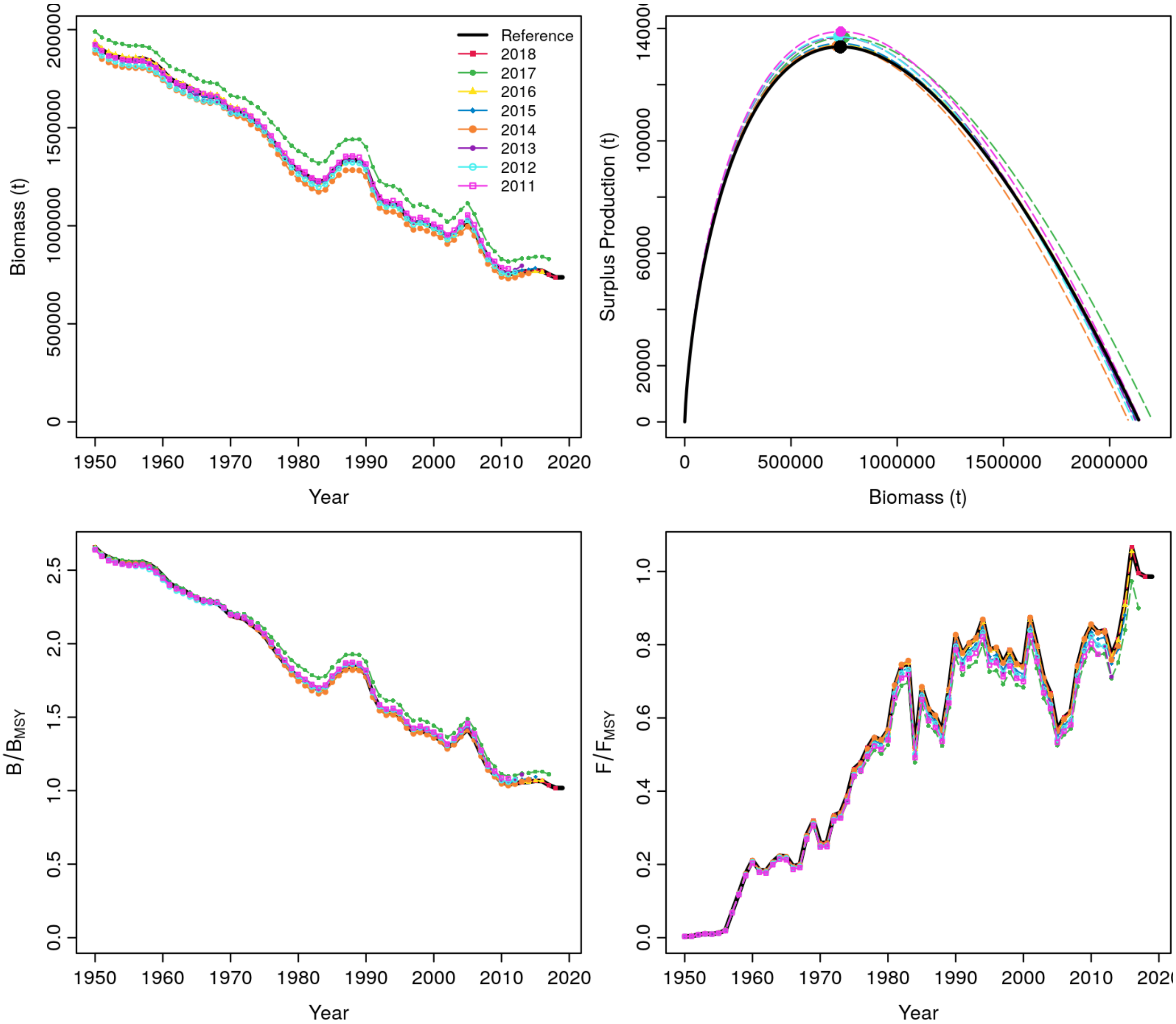

Figure 17. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (Scenario S3). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

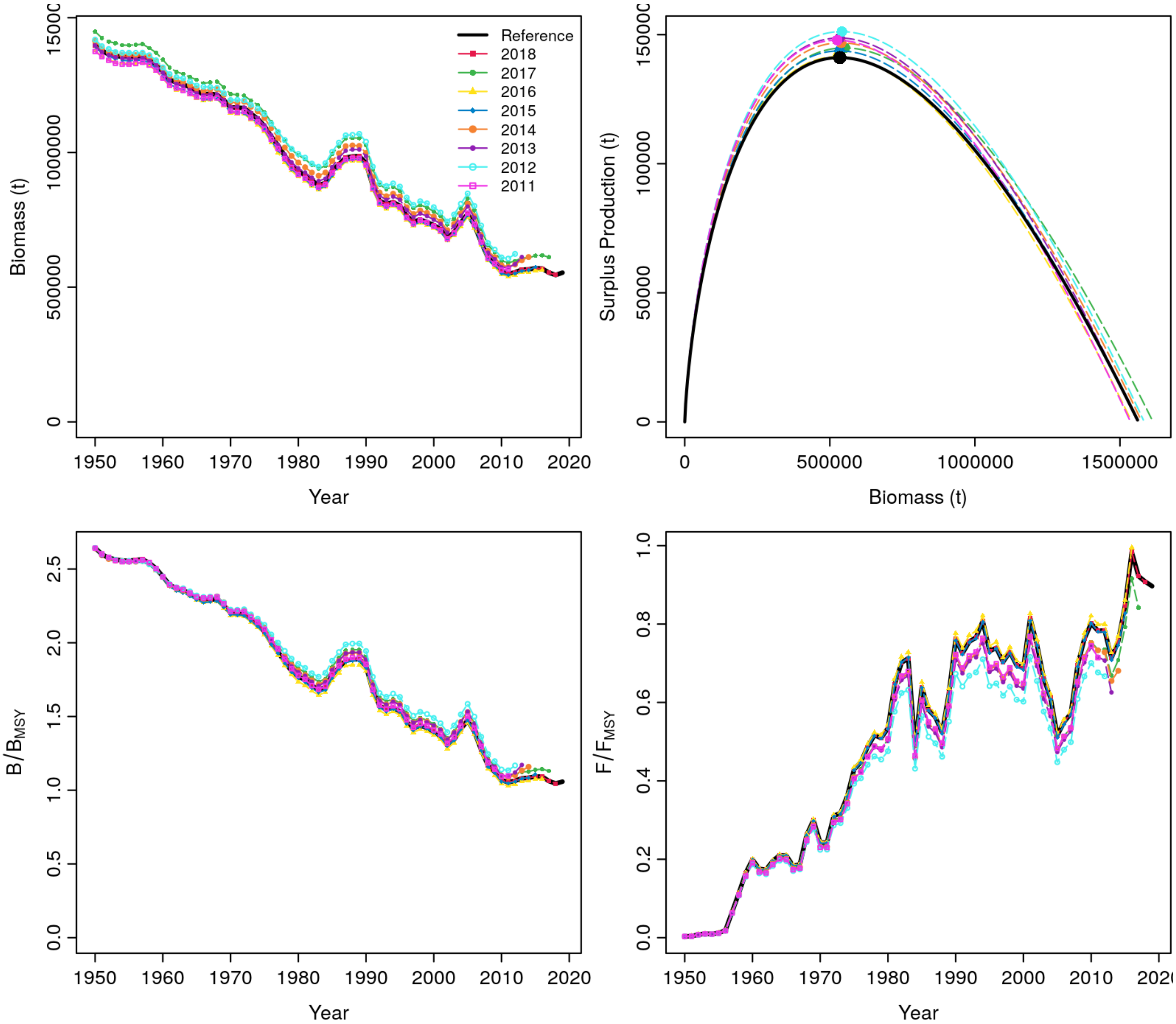

Figure 18. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (Scenario S4). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

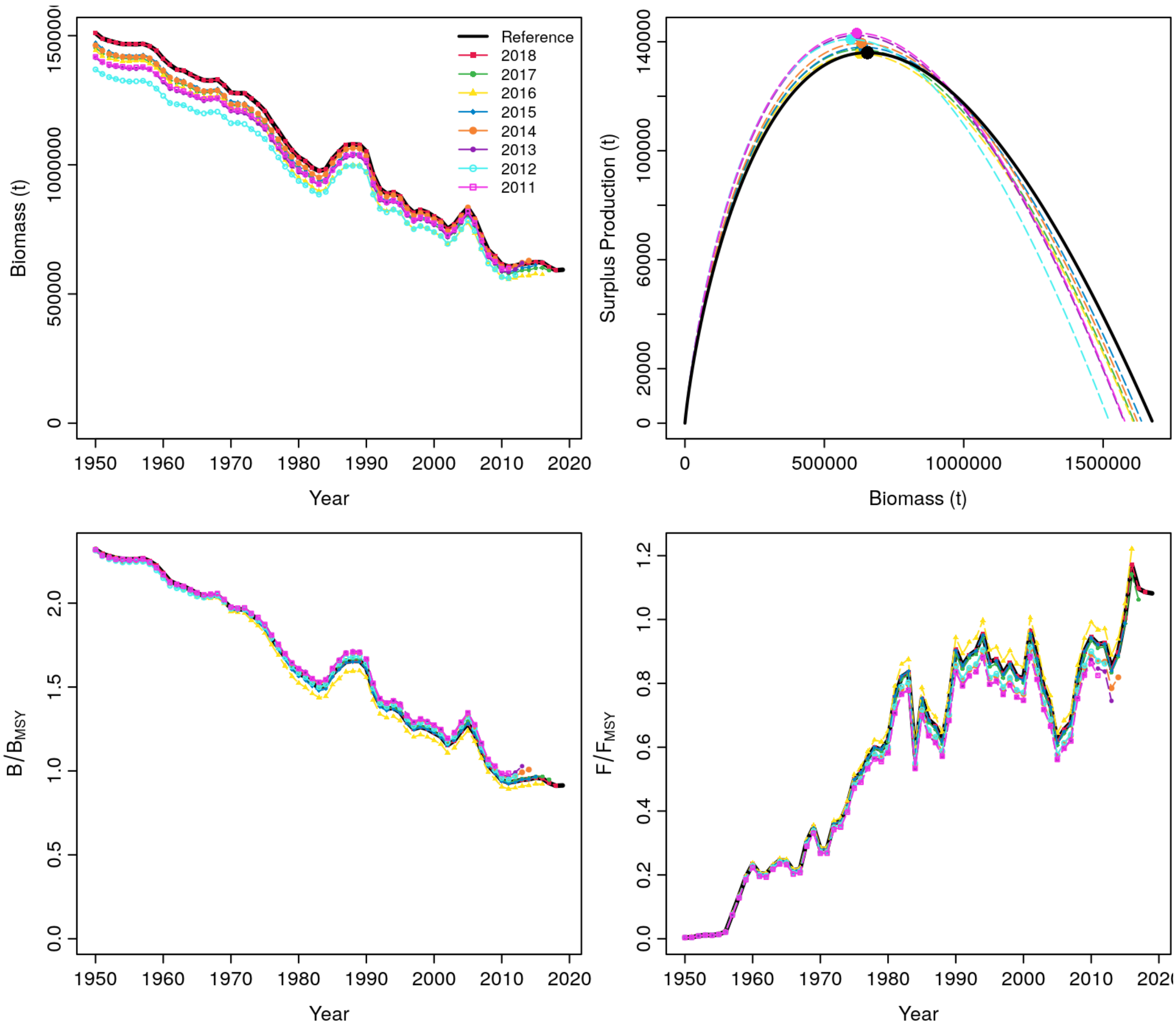

Figure 19. Retrospective analysis for stock biomass (t), surplus production function (maximum = MSY), B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model JABBA for Atlantic yellowfin tuna (Scenario S5). The label "Reference" indicates the base case model fits to the entire time series 1950-2018. The numeric year label indicates the retrospective results from the retrospective 'peel', sequentially excluding CPUE data back to 2010.

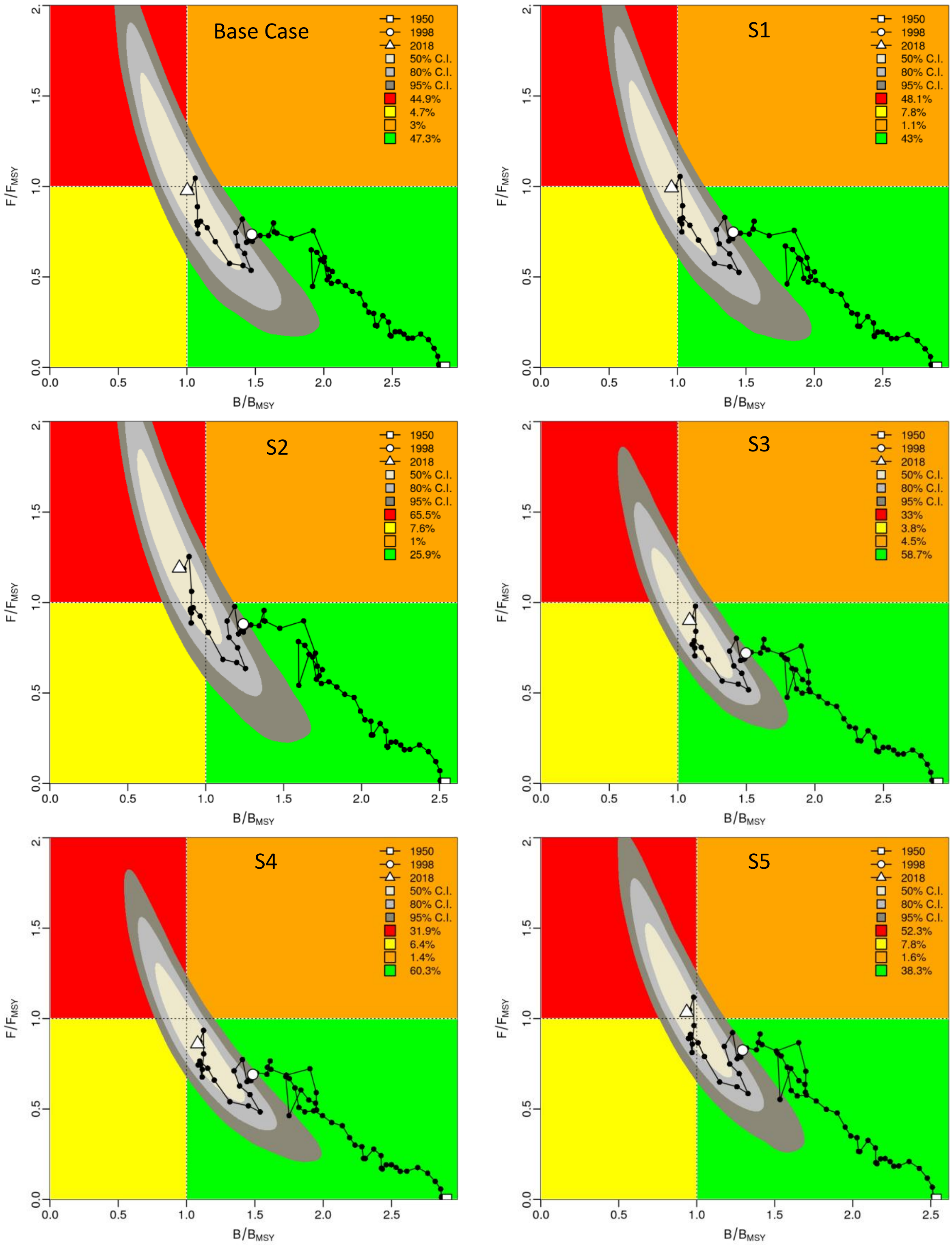

Figure 20. Kobe phase plot showing estimated trajectories (1950-2018) of B/B_{MSY} and F/F_{MSY} for the Bayesian state-space surplus production model for the Atlantic yellowfin tuna. Different grey shaded areas denote the 50%, 80%, and 95% credibility interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

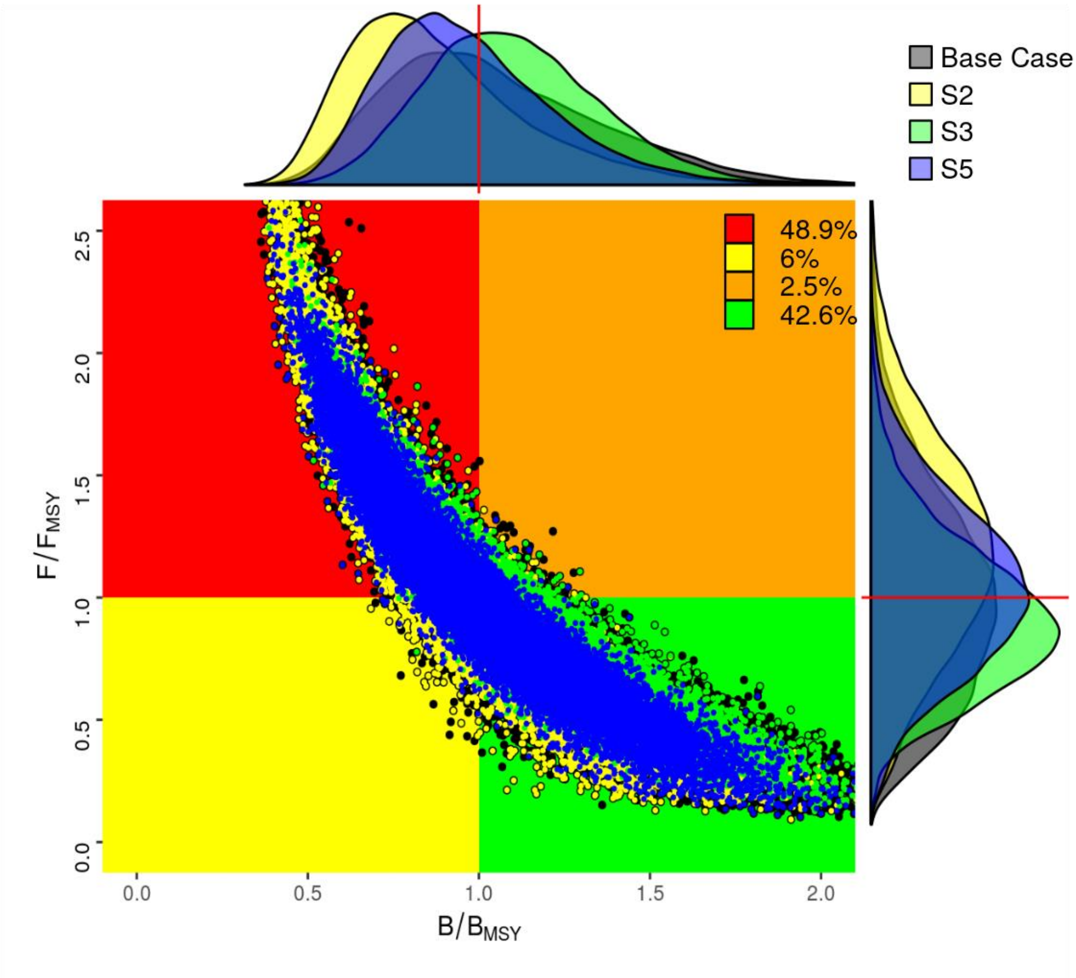

Figure 21. Kobe phase plot showing the combined posterior of final scenarios (Base Case, S2, S3 and S5) of B/B_{MSY} and F/F_{MSY} (1950-2018) for the Bayesian state-space surplus production model for the Atlantic yellowfin tuna. The probability of terminal year points falling within each quadrant is indicated in the figure legend.