A multivariate lognormal Monte-Carlo approach for estimating structural uncertainty about the stock status and future projections for Indian Ocean Yellowfin tuna

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Summary

This paper presents a multivariate lognormal (MVLN) Monte-Carlo approach to produce Kobe phase plots and Kobe II projection matrices for range of fixed catch scenarios from the 2018 Indian Ocean yellowfin tuna reference grid of Stock Synthesis models. First, we present Kobe-phase plots for the current stock status that compare within-model uncertainty estimates for a single reference case model to the structural uncertainty estimates from a reference grid of 24 models. The Kobe phase plot results portrait a more pessimistic stock status for the reference case model (94.3% overfished) compared to the uncertainty grid of 24 Stock Synthesis model configurations (83.9% overfished), which captures a wider range of plausible outcomes along SSB/SSB_{MSY} axis. Projections were conducted based on the 2018 reference grid models for fixed catch scenarios, ranging from 60-120% of the 2017 catch. These projections predict that a 20% reduction of current catches would is required to achieve MSY-based targets by 2027 and a reduction by at least 15% is required to prevent a severe stock collapse by 2024. Our results generally support previous findings that structural uncertainty across models is often more important to capture than the often narrower within model uncertainty, given that the grid comprise an adequate range of plausible alternative configurations of the reference case model. A potential advantage of the MVLN approach over the bootstrap and MCMC routines is that it reduces the computing time, thereby enabling rapid generation Kobe phase plots for advice during typically time constraint assessment meetings.

Keywords: *Stock Synthesis, inverted Hessian, model grid, delta-method, covariance matrix*

Introduction

The Kobe phase plot and the Kobe II strategy matrix (K2SM) are key stock assessment outputs for management advice within tuna Regional Fisheries Management Organizations, which both require translating the estimated uncertainty about the stock status into probabilistic statements (Kell et al., 2012). For both outputs, the key quantities of interest are typically the ratios spawning stock biomass (*SSB*) and fishing mortality (*F*) relative to their

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reference values SBB_{MSY} and F_{MSY} at levels that can produce the Maximum Sustainable Yield (MSY), respectively. The Kobe phase plot depicts the current stock status in terms of $SSB_{\mathrm{y}}/SSB_{\mathrm{MSY}}$ on the *x*-axis and $F_{\mathrm{y}}/F_{\mathrm{MSY}}$ on the *y*-axis. The plot is divided into four quadrants, defined for the stock biomass and fishing mortality relative to SSB_{MSY} and F_{MSY}, respectively. The color-coding is green if $SSB_{\mathrm{y}}/SSB_{MSY} > 1$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}} < 1$, $SSB_{\mathrm{y}}/SSB_{MSY} > 1$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}} > 1$, yellow if $SSB_{\mathrm{y}}/SSB_{MSY} < 1$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}} < 1$ if and red if $SSB_{\mathrm{y}}/SSB_{MSY} < 1$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}} > 1$. The construction of the K2SM, requires the generation of forward projected stock status under a series of fixed catch scenarios. The fixed catch scenarios are then assessed against some target probably that $SSB > SBB_{\mathrm{MSY}}$ and $F < F_{MSY}$ over the projection horizon (e.g. 10 years).

There are a number of options to generate the joint posterior distributions of plausible outcomes of $SSB_{\mathrm{y}}/SSB_{MSY}$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}}$ as a basis for estimating the probabilities of the stock falling into the respective quadrant of the Kobe phase plot. Commonly used approaches to do so include: (i) bootstrap or Markov Chain Monte-Carlo (MCMC) methods to estimate the within model uncertainty (e.g. Walter et al., 2019), (ii) developing a large grid of models to derive the Kobe posterior distribution from a sufficiently large number of point estimates $SSB_{\mathrm{y}}/SSB_{MSY}$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}}$ (e.g. $n > 500$) and (iii) a hybrid approach of joining MCMC or bootstrap derived posteriors from alternative model runs to capture both across- and within model uncertainty (Walter et al. 2019). However, in integrated age-structured stock assessment models, such as Stock Synthesis (Methot and Wetzel, 2013), these methods are computationally intense and time consuming as they require to first invert Hessian matrix and then refitting the model (bootstrap) or running sufficiently long MCMC chains (Magnusson et al., 2013; Maunder et al., 2006) or to fit a large number of grid models. This renders them as challenging tasks to complete during typically time-constrained stock assessment meetings.

The situation was not different at the 20th IOTC Working Party on Tropical tuna (WPTT) in 2018, where a preliminary stock assessment for yellowfin tuna (*Thunnus albacares*) in the Indian Ocean was presented (Fu et al., 2018a). The assessment was implemented using the Stock Synthesis software with the inclusion of fishery data up to 2017. The WPTT agreed to adopt a reference grid of 24 models to capture major sources of uncertainty and to assist the formulation of scientific advice. In addition, one of the 24 models was selected as a reference case model for the purpose of conducting more detailed model diagnostic tests. However, due to time constraints it was not feasible to generate posteriors of $SSB_{\mathrm{y}}/SSB_{MSY}$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}}$ based on the computational intense MCMC or bootstrap techniques. Instead of probabilistic statements about the likely stock status, the 2018 stock status was therefore classified as overfished and is subject to overfishing based on the point estimate medians of $SSB_{\mathrm{y}}/SSB_{MSY} = 0.83$ $F/F_{\mathrm{MSY}} = 1.20$, respectively. The future projections of constant catch scenarios, which were conducted after the WPTT (Fu et al., 2018b), were summarised in terms risk by calculating the probability of $SSB_{\mathrm{y}}/SSB_{MSY} < 1$ and $F_{\mathrm{y}}/F_{\mathrm{MSY}} > 1$ (i.e. not within the green quadrant) from the 24 point estimates for each projection year and catch scenario combination over a projection horizon of 10 years.

In this paper, we paper present Monte-Carlo approaches to produce Kobe phase plots and K2SM projection matrices based on the 2018 Indian Ocean Yellowfin tuna Stock Synthesis assessment using multivariate lognormal approximations for generating a joint posterior distribution of F/F_{msy} and SSB/SSB_{MSY}. First, we present the Kobe phase plots for the current stock status based on within model uncertainty estimates for the reference case model and structural uncertainty estimates across a grid of 24 model scenarios. We then constructed the K2SM by generating MVLN posterior distribution for each year and TAC combination of projections from the 24 models over the period 2018-2027.

Material and Methods

Stock Synthesis output data

The 2018 reference grid comprised of 24 Stock Synthesis model variations. Each model output was provided in a folder that was labelled according to the model name. The quantities of interest for estimation of structural uncertainty for 2017 across the grid models are the maximum likelihood estimates (MLEs) of $SSB_{i,2017}/SBB_{MSY,i}$ ("Bratio_") and $F_{i,2017}/F_{MSYi}$ ("*F*_") for model *i* in 2017, which can be conveniently imported from the Report.sso file into the software environment R with the SS_output() function from the R package 'r4ss' (Taylor et al., 2013). The reference case model included additional output of standard errors (SEs) and parameter correlation coefficients (ρ) in the form of the Covar.sso file as a result of inverting the Hessian matrix of the Stock Synthesis model.

Projections had been conducted for a 10-year forecast horizon (2018–2027) for all grid models for 11 constant catch scenarios. The 11 investigated constant catch scenarios represented 60% to 120% of the 2017 a total of 409,567t (in increment of 5% until 100% and with an increment of 10% afterwards). The projections assumed deterministic recruitment from the stock recruitment relationship. The Stock Synthesis projection output included the Report.sso, CompReport.sso and Forecast-report.sso files for each considered fixed catch, which were saved in subdirectories of the respective grid model folder. For the purpose of this study we developed a grepping function to extract the projected MLEs $SSB_{i,y}/SBB_{MSY,i,j}$ and $F_{i,y}/F_{MSYi,j}$ for model *i* and constant catch scenario quota *j* in projection year *y* into a data frame for further processing.

Generating delta-MVLN Kobe posteriors for the reference case model

The delta-Multivariate log-Normal' (delta-MVLN) estimator (Walter and Winker, 2019) infers within-model uncertainty from maximum likelihood estimates (MLEs), standard errors (SEs) and the correlation of the untransformed quantities F/F_{MSY} and SSB/SSB_{MSY}. These quantities are derived with Stock Synthesis using the delta-method to calculate the asymptotic variance estimates from the inverted Hessian. To generate Kobe posteriors from a delta-MVLN distribution requires the means and the variance-covariance matrix (VCM) of $\log(SSB/SSB_{\mathrm{MSY}})$ and $\log(F/F_{MSY})$. Let $u = SSB/SSB_{\mathrm{MSY}}$ and $v = F/F_{MSY}$ and $x = \log(u)$ and $y = \log(v)$, then the VCM has the form:

$$VCM_{x,y} = \begin{Bmatrix} \sigma_x^2 & cov_{x,y} \\ cov_{x,y} & \sigma_y^2 \end{Bmatrix} \quad (1)$$

where σ_x^2 is the variance of *x*, σ_y^2 is the covariance of *y* and $cov_{x,y}$ is the covariance of *x* and *y*. The quantities that can be directly extracted from Stock Synthesis are: (1) MLEs, asymptotic standard errors (SE) and correlation ρ of SSB/SSB_{MSY} and F/F_{MSY}.

The construction of the $VCM_{x,y}$ therefore requires to conduct a few normal to lognormal transformations. First, we approximate σ_x^2 and σ_y^2 as:

$$\sigma_x^2 = \log\left(1 + \left(\frac{SE_u}{u}\right)^2\right) \quad \text{and} \quad \sigma_y^2 = \log\left(1 + \left(\frac{SE_v}{v}\right)^2\right) \quad (2)$$

where SE_u and SE_y is the asymptotic standard error estimate for $u = SSB/SSB_{MSY}$ and $v = F/F_{MSY}$. Second, the covariance of *x* and *y* can then be approximated on log-scale by:

$$cov_{x,y} = \log\left(1 + \rho_{u,v}\sqrt{\sigma_x^2\sigma_y^2}\right) \quad (3)$$

where $\rho_{u,v}$ denotes the correlation of *u* and *v*.

To generate the desired Kobe posterior of for SSB/SSB_{MSY} and F/F_{MSY}, we use a multivariate random generator, available in the R package '*mvtnorm*', to obtain a large number (n_{sim} = 10,000) of *x* and *y* pairs, such that

$$Kobe_{x,y} = MVN\left(\mu_{x,y}, VCM_{x,y}\right) \quad (4)$$

where $\mu_{x,y}$ is the vector of the MLEs *x* and *y*. The joint MVLN distribution of SSB/SSB_{MSY} and F/F_{MSY} is then obtained as the exponential of $Kobe_{x,y}$.

To generate the Kobe posterior for 2017, we applied function ss_deltaMVLN() function presented in Winker et al. (2019), which readily includes a grep function to extract desired Stock Synthesis estimates (MLEs, SEs, ρ). The Kobe posterior was generated from 10,000 Monte-Carlo simulations. No covariance estimates (Covar.sso) are currently available for the projection, so that the delta-MVLN could not be applied to construct the K2SM for reference case model (c.f. Walter and Winker, 2019).

Generating MVLN Kobe posteriors from point estimates of the reference grid

The MVLN approach to estimate the structural uncertainty in the form of a Kobe posterior only requires the MLE point estimates of $SSB_{i,y}/SBB_{MSY,i,j}$ and $F_{i,y}/F_{MSYi,j}$ for model *i* and catch scenario *j* in projection year *y*. For the Kobe posterior for the final assessment year 2017 the subscript *j* will always represent the current catch and can be therefore omitted. To generate the desired Kobe posterior of $SSB_{i,y}/SBB_{MSY,i,j}$ and $F_{i,y}/F_{MSYi,j}$, we again make use of the multivariate random generator (R package '*mvtnorm*') to obtain a large number (n_{sim} = 10,000) of *x* and *y* pairs, such that

$$Kobe_{x,y} = MVN(\mu_{x,y}, VCM_{x,y}) \quad (5)$$

where in this case $\mu_{x,y}$ represents the medians of log($SSB_{i,y}/SBB_{MSY,i,j}$) and log($F_{i,y}/F_{MSYi,j}$) for each quota j and projection year y across the 24 models and $VCM_{x,y}$ is the corresponding covariance of log($SSB_{i,y}/SBB_{MSY,i,j}$) and log($F_{i,y}/F_{MSYi,j}$). For the construction of the Kobe posteriors, the 24 reference grid model were assigned relative weightings of 75% for the “q1” CPUE scenario compared to 25 % for the “q2” scenario (IOTC–WPTT20 2018). This was achieved by replicating the MLE estimates at a ratio of 3:1 prior to the calculations of $\mu_{x,y}$ and $VCM_{x,y}$.

To prevent implausible outcomes of log($SSB_{i,y}/SBB_{MSY,i,j}$) and log($F_{i,y}/F_{MSYi,j}$) during the projection phase, we imposed a number of penalties (c.f. Walter and Winker 2019). The primary problem is that high fixed total allowable catch (TAC) projections can often be unsustainable, even in the near future, and lead to stock collapses ($SSB_{y,i,j,} < 0$), after which the Stock Synthesis trajectories may start to vary between nonsensical extreme values. As a result, the $VCM_{x,y}$ can be composed of inflated variances together highly negative correlation structure. The imposed penalties set all $SSB_{i,y}/SBB_{MSY,i,j}$ MLEs at and post collapse to a small constant ‘B_{floor}’ of 0.01 and the corresponding $F_{i,y}/F_{MSYi,j}$ MLEs to a ‘$F_{ceiling}$’ of 10. In addition, the maximum variances σ_x^2 and σ_y^2 and correlation coefficients ρ penalized to not exceed increase by more than a factor of five relative to the ‘reference’ $VCM_{x,y}$ for the final assessment year.

Results and Discussion

The estimated stock status trajectories from reference grid show the typical characteristics of a one-way downhill trip (Hilborn, 1979). Biomass levels of SSB_y/SSB_{MSY} have been continuously decreasing under a continuous increase in fishing mortality F_y/F_{MSY} (Figure 1). The resulting stock status for the final year is pessimistic, but even more so for the reference case model (94.3% in red) compared to the uncertainty grid of 24 model scenarios (83.8% in red), associated with a 0% and 1.3% probability, respectively, that both biomass and exploitation levels are currently sustainable (Figure 1). The within-model uncertainty indicated F_{2017}/F_{MSY} was imprecisely estimated by the model. Compared to the typical ‘banana-like’ shape of the reference grid MVLN posterior, the delta-MNLN posterior for the reference case showed a lack of correlation between SSB_{2017}/SSB_{MSY} and F_{2017}/F_{MSY}, associated with narrower range of plausible outcomes along SSB/SSB_{MSY} axis.

The medians of the MVLN projection posteriors for the reference grid (‘chicken feet plot’) predicted that the stock is likely to crash by 2026 if catches were maintained at current levels of 409,567t, and that a catch reduction by 20% would be required to achieve biomass and fishing mortality levels that can sustain MSY (Figure. 3). The MVLN projection posteriors for 2020 and 2027 are shown for each of the 11 fixed catch projections in Figure 4. By 2020, the MLVN posteriors of $SSB_{2020,j}/SSB_{MSY}$ and $F_{2020,j}/F_{MSY}$ under constant catch j show a high degree overlap, whereas by 2027, there is a clear separation between the projection posteriors for the constant catch projections of 60%-85% and 90%-110% of current catch levels, respectively (Figure 4). Constant catch projections above 85% of current catch had largely crashed ($SSB_{2027,j}/SSB_{MSY} \sim 0.01$). The 2027 projection posterior for 85% of current catch falls mostly into the red quadrant of the Kobe phase plot but remains above half of SSB_{MSY} (Figure 4). The resulting stock status probabilities suggest that the stock status would be classified sustainable (green) for constant catches at 60% - 70% of current catch, rebuilding (yellow) under 76% - 80% and overfished with overfishing occurring (red) under constant catches of 85% and larger. Those constant catch scenarios that were predicted to rebuild the stock in 2020 (76% - 80% of current catch) would achieve sustainable by 2027.

For the here considered intervals between constant catch scenarios, the projected stock status classification based on the MVLN projection posteriors does not differ from the classification that was inferred from the probabilities of forecasted 24 point estimated falling within the respective Kobe quadrants (Fu et al. 2018b; Table 1). On closer inspection, however, the MLVN projection posteriors show a gradual change in probabilities, whereas point estimate probabilities resulted in repeating the same probability twice in some instances (Table 1). This can be attributed to the limited number of possible outcomes of 24 binary draws compared to 10,000 for generating the MVLN posterior.

Arguably, a gradual change in probabilities, as predicted from the MVLN projection posteriors, appears more plausible, and is probably less sensitive to choice of interval between fixed catches. A potential advantage of the MVLN approach over the bootstrap and MCMC routines is that it reduces the computing time, thereby enabling rapid generation Kobe phase plots for advice during typically time constraint assessment meetings. Our results suggest that the inherent structural uncertainty is unlikely be adequately represented by the within-model uncertainty estimates of a single reference model. Considering alternative model configurations is therefore advisable.

A caveat of the MVLN grid approach is, however, that it uncertainty about the parameter estimates, which may in this case lead to underestimating the uncertainty about current fishing mortality levels, in particular toward values of $F/F_{MSY} >> 1$ (Figure 2). Potential causes for the seemingly inflated asymptotic variance estimates of F/F_{MSY} in the reference case model may be related to overparameterization and regularization issues, for example in selectivity parameters due to limited and conflicting information in the length data (Monnahan et al., 2019). However, at least part of the poor precision can probably be attributed to the well documented challenges associated with a 'one-way downhill trip' situation, because the lack of contrast in the continuously declining biomass typically contains limited information about productivity and the scale of absolute biomass relative to the 'known' catch (Hilborn, 1979; Hilborn and Walters, 1992). The 'one-way downhill trip' of Indian Ocean yellowfin abundance is therefore inherently associated with high uncertainty about the stock being overfished and may be undergoing overfishing until such time the ongoing decline can be reversed.

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Table 1. Comparison of Kobe II Strategy Matrices derived from the 2018 yellowfin tuna reference grid of 24 Stock Synthesis models, based on MVLN posteriors from Monte-Carlo simulations (top) and probabilities directly calculated from the 24 model point estimates (bottom), after Fu et al. (2018b). Probability of violating the MSY-based target reference points, $SSB < SSB_{MSY}$ and $F > F_{MSY}$, for constant catch projections are presented for 2020 (3 years) and 2027 (years). Constant catches represent percentages (65%-110%) of the 2017 catch (409,567t). The colour-coding classifies the stock status according the Kobe quadrant based the highest probabilities.

Reference point and projection timeframe	Alternative catch projections (relative to the catch level from 2017) and probability (%) of violating MSY-based target reference points (Btarg = SSB_{MSY}; Ftarg = F_{MSY}) based on the MVLN posterior for reference grid								
	65% (266,218t)	70% (286,697t)	75% (307,175t)	80% (327,654t)	85% (348,132t)	90% (368,610t)	95% (389,089t)	100% (409,567t)	110% (450,523t)
$SSB_{2020} < SSB_{MSY}$	0.41	0.48	0.57	0.67	0.77	0.85	0.92	0.96	1.00
$F_{2020} > F_{MSY}$	0.04	0.12	0.27	0.43	0.58	0.72	0.85	0.95	1.00
$SSB_{2027} < SSB_{MSY}$	0.01	0.03	0.06	0.23	0.83	1.00	1.00	1.00	1.00
$F_{2027} > F_{MSY}$	0.01	0.07	0.17	0.41	0.99	1.00	1.00	1.00	1.00
	Alternative catch projections (relative to the catch level from 2017) and probability (%) of violating MSY-based target reference points (Btarg = SSB_{MSY}; Ftarg = F_{MSY}) based on binary probabilities of point estimates from the refenrence grid								
	65% (266,218t)	70% (286,697t)	75% (307,175t)	80% (327,654t)	85% (348,132t)	90% (368,610t)	95% (389,089t)	100% (409,567t)	110% (450,523t)
$SSB_{2020} < SSB_{MSY}$	0.48	0.48	0.73	0.85	0.85	0.96	0.98	0.98	1.00
$F_{2020} > F_{MSY}$	0.04	0.12	0.25	0.48	0.56	0.79	0.96	0.98	1.00
$SSB_{2027} < SSB_{MSY}$	0.08	0.08	0.25	0.42	0.56	0.79	0.98	1.00	1.00
$F_{2027} > F_{MSY}$	0.06	0.08	0.23	0.42	0.63	0.85	1.00	1.00	1.00

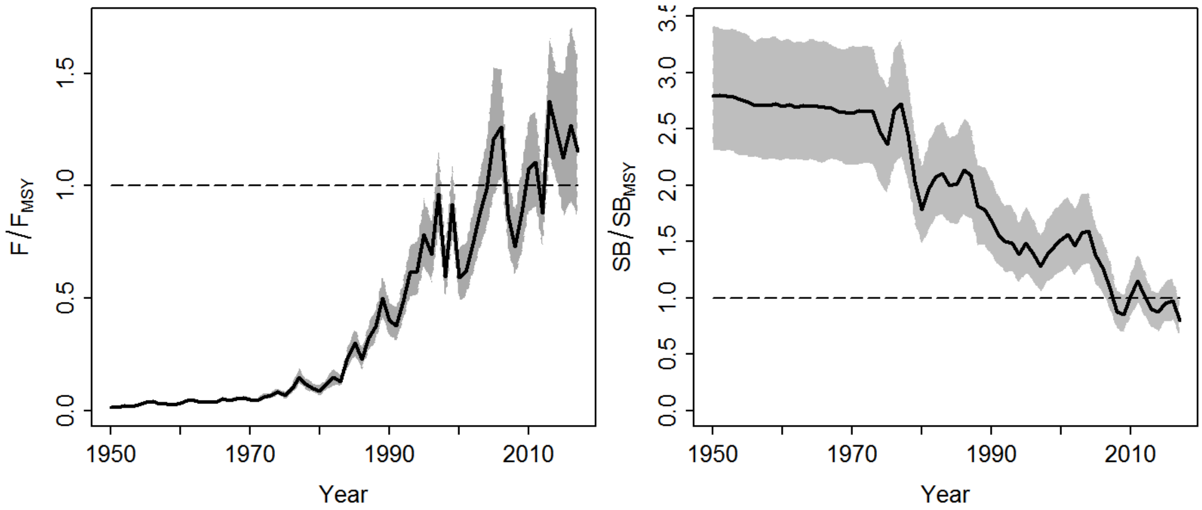

Figure 1. Estimated stock status trajectories of F/F_{MSY} and SSB/SSB_{MSY} (1950-2017) from reference grid, showing the median (solid line) and 95% credibility intervals (grey shading) from MVLN posteriors.

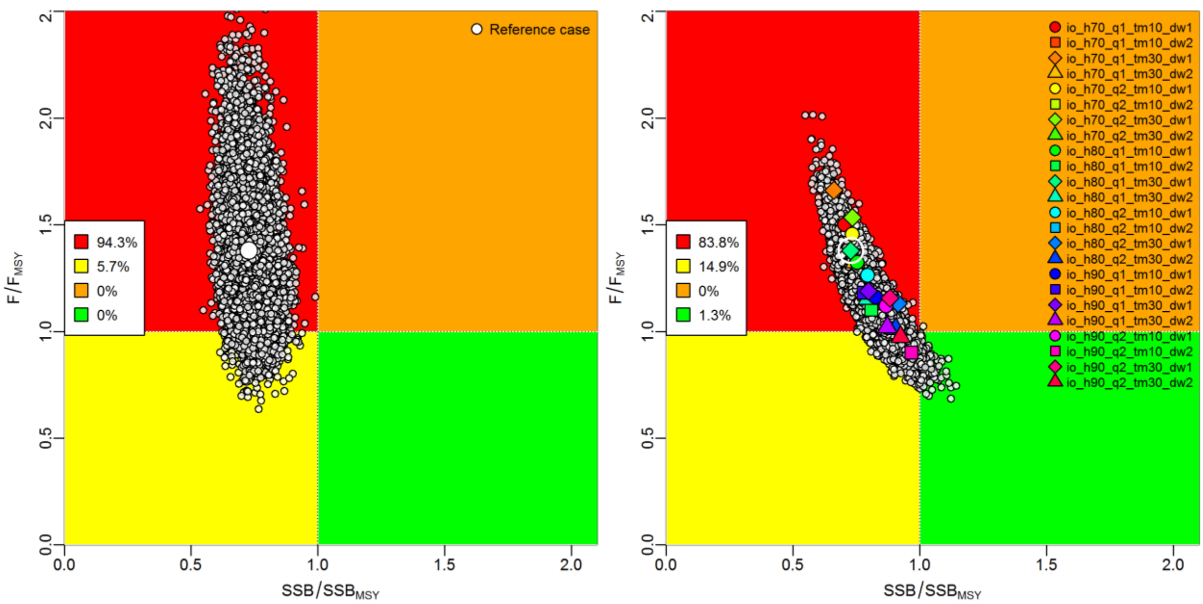

Figure. 2. Kobe phase plots comparing delta-MVLN posterior distribution (grey dots) for the reference case model (left) and the reference grid MVLN approximation (right) for the 4th quarter of the final assessment year 2017. Color-coded circles denote the point estimates from individual model runs. The probability of falling within each quadrant is indicated in the figure legend. The thin white circle in the right plot highlights the location of the reference case model within the reference grid.

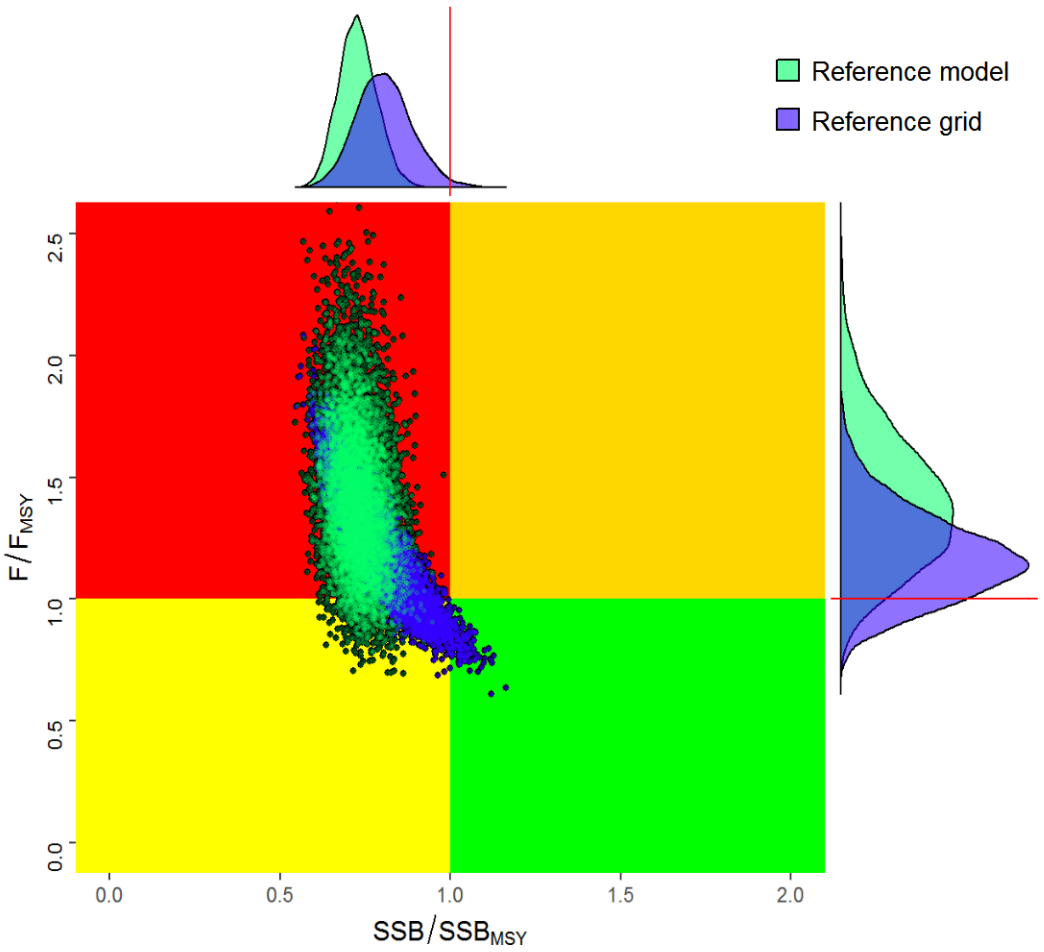

Figure. 3. Marginal Kobe posterior phase plot comparing MVLN posterior distributions of *SSB/SSB$_{MSY}$* and *F/F$_{MSY}$* in the 4th quarter of 2017 from the single reference case model and reference grid of Stock Synthesis models for in Indian Ocean yellowfin tuna.

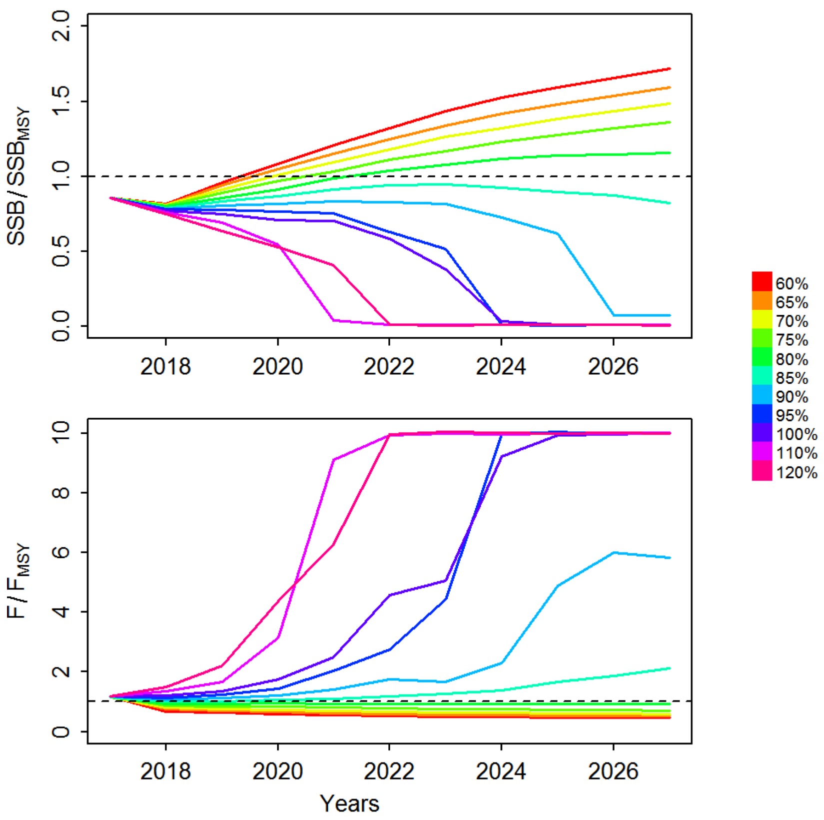

Figure. 4. Medians of MVLN Kobe posteriors show the projection trajectories of *SSB/SSB$_{MSY}$* and *F/F$_{MSY}$* under alternative fixed catch scenarios ('chicken feet plots'). Constant catches represent percentages (65%-110%) of the 2017 catch (409,567t).

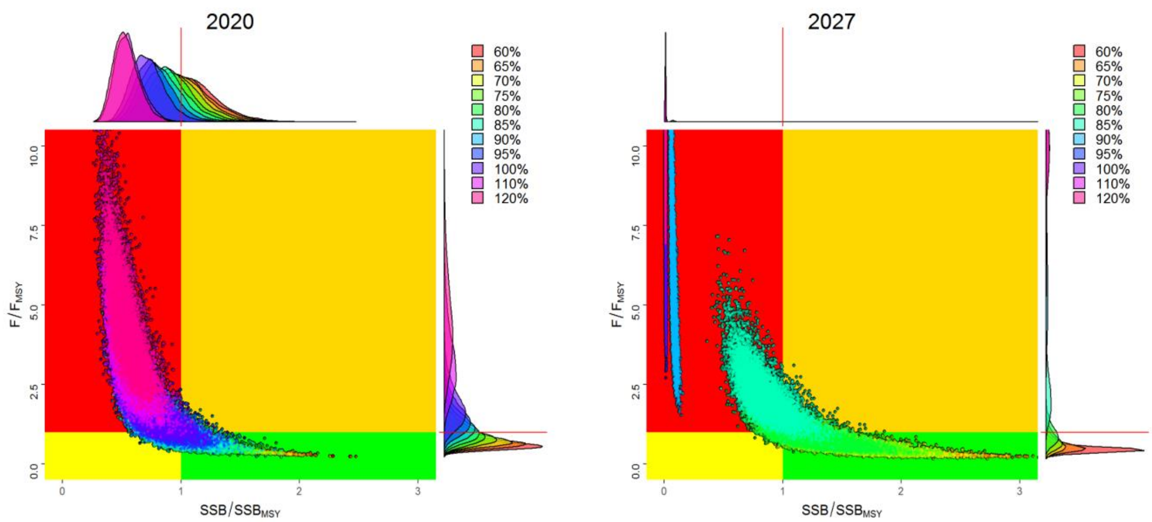

Figure 5. Marginal Kobe posterior phase plots comparing MVLN projection posteriors of *SSB/SSB$_{MSY}$* and *F/F$_{MSY}$* for the years 2020 and 2027across alternative constant projection scenarios in years 2020 and 2027. The MVLN projection posteriors were based on the 2018 reference grid of Stock Synthesis models for in Indian Ocean yellowfin tuna.

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