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STOCK ASSESSMENT OF WESTERN ATLANTIC SAILFISH (*ISTIOPHORUS PLATYPTERUS*) USING A BAYESIAN STATE-SPACE SURPLUS PRODUCTION MODEL

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SUMMARY

We present results of the stock assessment of the western Atlantic sailfish stock. The assessment consisted of fitting a Bayesian state-space surplus production model to catch and CPUE data. The catch time series is derived from the ICCAT database, relative abundance indices for sailfish consisted of standardized catch-per-unit effort (CPUE) for Japan, Brazil, U.S. and Venezuela, including longline, recreational and gillnet fisheries. One production model that included all input CPUE indices and prior mean values was developed. Model estimates for the biomass of sailfish in the western Atlantic Ocean was 26,418 metric tons for 2014, which is above the estimated BMSY of 20,086 metric tons. The estimated harvest rate in 2014 was 0.025, which is lower than the estimated HMSY of 0.065. Based on model outputs the western Atlantic sailfish population biomass has slightly declined over the available time series but above of BMSY and has remained stable since middle 1980s. In addition, it is very unlikely that western Atlantic sailfish population was being fished in excess of its optimal equilibrium harvest rate in 2014.

RÉSUMÉ

Le présent document fait état des résultats de l'évaluation du stock de voilier de l'Atlantique Ouest. L'évaluation a consisté à ajuster un modèle de production excédentaire état-espace de type bayésien aux données de CPUE et de capture. La série temporelle de capture provient de la base de données de l'ICCAT et les indices d'abondance relative du voilier étaient composés de la capture par unité d'effort (CPUE) standardisée du Japon, du Brésil, des États-Unis et du Venezuela, incluant les pêcheries palangrières, récréatives et au filet maillant. Un modèle de production, qui incluait l'ensemble des indices de CPUE d'entrée et les valeurs moyennes préalables, a été développé. Selon les estimations du modèle, la biomasse du voilier dans l'océan Atlantique occidental s'élevait à 26.418 tonnes en 2014, ce qui dépasse la B_{PME} *estimée de 20.086 tonnes. Le taux de capture estimé en 2014 s'élevait à 0,025, soit un niveau inférieur au* H_{PME} *estimé de 0,065. Selon les résultats du modèle, la biomasse de la population de voilier de l'Atlantique Ouest a baissé au cours de la série temporelle disponible, mais est supérieure à* B_{PME} *et est restée stable depuis le milieu des années 80. En outre, il est très peu probable que la population de voilier de l'Atlantique Ouest ait été surpêchée au-delà de son taux de capture en conditions d'équilibre optimal en 2014.*

RESUMEN

En este documento se presentan los resultados de la evaluación de stock del pez vela del Atlántico occidental. La evaluación consistió en ajustar un modelo de producción excedente bayesiano de estado-espacio a los datos de captura y de CPUE. La serie temporal de captura se calculó a partir de la base de datos de ICCAT, y los índices de abundancia relativa de pez vela consisten en la captura por unidad de esfuerzo (CPUE) estandarizada para Japón, Brasil, Estados Unidos y Venezuela, incluyendo las pesquerías de palangre, de recreo y de redes de enmalle. Se desarrolló un modelo de producción que incluía todas los valores de entrada de la CPUE y también se desarrollaron los valores medios de la distribución previa. Las estimaciones del modelo para la biomasa de pez vela del Atlántico occidental se situaron en 26.418 t para 2014, lo que se sitúa por encima de la B_{RMS} *estimada de 20.086 t. La tasa de*

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captura estimada en 2014 era de 0,025, cifra inferior a la H_{RMS} *estimada de 0,065. Basándose en los resultados del modelo, la biomasa de la población del pez vela del Atlántico occidental ha descendido ligeramente durante la serie temporal disponible, pero está por encima de* B_{RMS} *y ha permanecido estable desde mediados de los 80. Además, es muy poco probable que la población de pez vela del Atlántico occidental se haya pescado por encima de su tasa de captura en equilibrio óptima en 2014.*

KEYWORDS

Sailfish, Western Atlantic, stock assessment, Bayesian, state-space model

Introduction

Sailfish (*Istiophorus platypterus*) is an epipelagic species with a pan-tropical distribution. It is the least oceanic of the Atlantic billfishes, it shows a strong tendency to approach continental coasts, islands and reefs (Nakamura, 1985). The impact of fishing on billfish stocks in the Atlantic Ocean is currently on focus of considerable international concern. Major recreational fisheries for billfishes (Istiophoridae) exist throughout the world's tropical oceans, thus placing them among the most sought-after big gamefish. Besides, although billfishes are not a target species, they are also caught in great numbers by commercial fisheries, including both industrial, such as the tuna longline and artisanal gillnet fisheries.

In 2009, the International Commission for the Conservation of Atlantic Tunas (ICCAT) carried out for the first time a stock assessment for Atlantic sailfish based on the two stock hypothesis scenario (western and eastern). Although the general conclusion of the assessment was that both sailfish stocks are overfished with evidence of overfishing, particularly on the east side, the results were interpreted with considerable caution due to data deficiencies and the resulting uncertainty in the assessment. This was supported by several alternative model runs, particularly for the west, indicated the biomass ratio B_{2007}/B_{MSY} both above and below 1.0. In addition, the results for the eastern stock were more pessimistic than those for the western stock in that more of the results indicated recent stock biomass below B_{MSY}.

Here we applied a Bayesian state-space surplus production model (SPM) to assess the western sailfish population in the Atlantic Ocean using updated catch and effort data through 2014. The Bayesian framework provides direct estimates of parameter uncertainty that are straightforward to interpret. Bayesian posterior distributions for quantities of management interest using the Markov chain Monte Carlo (MCMC) algorithm were also developed.

Material and Methods

Fishery data

Catch

The ICCAT secretariat estimates catch for many fleets and nations based on the best available information. Fishery catch data from 1961-2014 for assessing western Atlantic sailfish were obtained from the most recent report of the Scientific Committee for Research and Statistics (**Figure 1**).

Abundance indices

Catch and effort data were used to develop standardized catch-per-unit-of-effort (CPUE) time series, which were assumed to be proportional to population size and were used as relative indices of abundance. CPUE was standardized for many fishing fleets, including longline, recreational and artisanal drift gillnet fisheries across the western Atlantic Ocean. In the present analysis 9 standardized CPUE series from Japan, United States, Venezuela and Brazil were used (**Figure 2**).

Stock assessment model

Bayesian state-space SPMs were formulated to assess the western Atlantic sailfish population. State-space models are regarded as a powerful tool for modeling time-varying abundance indices because they simultaneously account for both process error and observation error (Meyer and Millar 1999, de Valpine 2002, Buckland *et al.* 2004). The process error can account for model structural uncertainty as well as natural variability of stock biomass due to stochasticity in recruitment, natural mortality, growth and maturation, while the observation error determines the uncertainty in the observed abundance index due to reporting error and unaccounted variations in catchability (Meyer and Millar 1999, Ono *et al.*, 2012).

We implemented the state-space models in JAGS (version 3.4.0) via the R2jags package in the statistical programming environment R (R Development Core Team 2013). In the present assessment, an existing state-space representation of the surplus production model using a Bayesian estimation framework developed by Meyer and Millar (1999) was applied. The production function was parameterized in the form of the generalized Pella and Tomlinson (1969) model:

(1) $$g(B_y)=\frac{r}{m}B_y\left(1-\left(\frac{B_y}{K}\right)^m\right)$$

where *r* is the intrinsic rate of population increase in year *y* and *K* is the biomass at the carrying capacity and *m* is a shape parameter that determines at which *B/K* ratio maximum surplus production is attained, which is commonly used as equivalent to MSY. If the shape parameter is one (*m*=1) the model reduces to the Schafer form, with the surplus production *g*(B_t) attaining MSY at exactly *K*/2. The Pella-Tomlinson model reduces to a Fox model if *m* approaches zero (*m*→ 0) resulting in maximum surplus production at ~ 0.37*K*.

Based on the parameterization by Meyer and Millar (1999), the process equation was rewritten into a stochastic population model with population state variables expressed as a proportion of the carrying capacity ($P_t = B_t/K$) (Equation 2). The biomass in the first year of the time series was assumed to be equal to *K* (i.e. $P_1 = 1$), which means that the population was unfished in 1961. The stochastic form of the process equation is given by:

(2) $$P_y=\left(P_{y-1}+rP_{y-1}\left(1-P_{y-1}{}^m\right)-\frac{C_t}{K}\right)e^{\eta_y-\frac{\sigma_\eta^2}{2}} \qquad y=1,2,3,...,n$$

where η_y is the process error, with $\eta_y \sim N(0,\sigma_\eta^2)$, *r* is the intrinsic rate of population increase, *K* denotes the unfished spawner biomass at theoretical carrying capacity, C_{y-1} is the catch in year *y*.

The model is formulated to accommodate multiple CPUE indices for each fishery *f*. The observation error model connects the state process (Equation 2) to CPUE index for year *y* and fishery *f*, assuming CPUE is proportional to biomass (Equation 3). The observation equation is given by:

(3) $$I_{f,y}=q_{f,y}EB_{f,y}e^{\varepsilon_y-\frac{\sigma_\varepsilon^2}{2}} \qquad y = 1, 2,\ldots, n.$$

where, q_f is the catchability coefficient for fishery *f* and ε_y is the observation error, with $\varepsilon_y \sim N(0,\sigma_\varepsilon^2)$.

The full Bayesian state-space SP projected over *n* years requires a joint probability distribution over all unobservable hyper-parameters $\boldsymbol{\theta}=\{K,r,q_{f,t}\}$ and the *n* process errors relating to the vector of unobserved states $\boldsymbol{\eta}=\{\eta_1,\eta_2,..\eta_y)$, together with all observable data in the form of the relative abundance indices $\mathbf{I}=\{I_{1,f},I_{2,f},..I_{y,f}\}$ (Meyer and Millar 1999). According to Bayes' theorem, it follows that joint posterior distribution over all unobservable parameters, given the data and unknown states, can be formulated as (Equation 4):

$$p(\theta \mid \eta, \mathbf{I}) = p(K)p(r)p(\sigma_{\eta}^{2})p(q_{f,t})p(\sigma_{\varsigma}^{2})p(\sigma_{\varepsilon}^{2}) \tag{4}$$
$$\times\, p(P_1 \mid \sigma_{\eta}^{2})\prod_{y=1}^{n} p(P_y \mid P_{y-1}, K, r, \sigma_{\eta}^{2}) \times \prod_{y=1}^{n} p(I_y \mid P_{t,} q_{f,t}, \eta_t, \sigma_{\varepsilon}^{2}, \sigma_{\zeta}^{2})$$

Biological reference points

For SPMs harvest management measures can be derived from Equation (1), including Maximum Sustainable Yield (MSY), the stock biomass at the end of the last year of the assessment period (B_{2014}); the stock biomass at which MSY is achieved (B_{MSY}); the fishing intensity corresponding to MSY (H_{MSY}); the harvest rate during the last year of the assessment period (H_{2014}); the ratio of the spawning stock biomass at the end of the last year of the assessment period to that at which MSY is achieved ($B_{2014}/B_{\mathrm{MSY}}$); and the ratio of H during the last year of the assessment period to that corresponding to MSY ($H_{2014}/H_{\mathrm{MSY}}$). These parameters were used for determining stock status.

The biomass required to produce MSY, B_{MSY} is given by:

$$B_{MSY} = K(m+1)^{\frac{-1}{m}}, \tag{2}$$

and corresponding harvest rate (H_{MSY}) is:

$$H_{MSY} = \frac{r}{m}\left(1-\frac{1}{m+1}\right), \tag{3}$$

where the harvest rate (H) is defined here as the ratio of catch to biomass.

Data weighting

Here we used the loess smoother method recommended by Francis (2011) which involves fitting a log-transformed CPUE index using loess smoothers and calculating the CV of the residuals of the fit of the smoother to the data (this is equivalent to saying that we expect the stock assessment model to fit the data as well as the smoother). High weight means that the observed is expected to be close to the estimated (so its CV will be small). The resulting CV for the 9 CPUE indices is presented in **Figure 3**. No change to input CV for each CPUE series, except for U.S. recreational fishery (1981-2015) (SCRS-2016-093) and Venezuelan drift-gillnet fishery (1991-2014) (SCRS-2016-075), which the resulting CVs were relatively low, 16.3% and 8%, respectively (**Figure 3**). For these CPUE indices, we applied a constant CV of 20% in order to scale up the annual CV to match the range of CVs estimated for the other input CPUE time series. This procedure was necessary because small CVs (lower than 20%) can substantially affect both model outputs and all statistical inference from the model (Mark Maunder[3], personal communication).

Prior distribution

In this study we assumed informative prior distributions for r and a non-informative for K. For r we used a lognormal distribution with mean 0.16 which is a little higher of the median (r close to 0.13) estimated by Carruthers and McAllister (2011) but with standard deviation equal to 0.25 in order to give more flexibility in parameter estimation. We used non-informative inverse gamma prior for the K (0.001, 0.001) and for the catchability parameter (0.001, 0.001). Process error (sigma) was fixed at 0.05 (see Ono et al., 2012 for details).

Convergence to posterior distribution

A critical issue in using MCMC methods is how to determine if random draws have converged to the posterior distribution. Convergence of the MCMC samples to the posterior distribution was checked by monitoring the trace and by diagnosing the autocorrelation plot. Gelman and Rubin (1992) and Heidelberger and Welch (1983) diagnostics as implemented in the R language (R Development Core Team, 2013) and the CODA package were also examined. In this study, three MCMC chains were used. The model was run for 1000,000 iterations, sampled with a thinning rate of 100 with a burn-in period of 200,000 for three chains.

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[3] Head of the stock assessment program of the Inter-American Tropical Tuna Commission.

Diagnostics of model fitting

The predicted CPUE indices for the model were compared to the observed CPUE to determine model fit. The estimates of production model can be problematic when the data are not informative about whether the population has a high K and a low r or vice versa (Hilborn and Walters 1992). The posterior correlation between model parameters was also examined in this regard.

Results

Catch

The total annual catch of western Atlantic sailfish showed an overall increase trend between 1961 and 2002 when the total catch peaked at 1,981 t (**Figure 1**). In the following years, however, the catches rapidly decreased achieving 615 t in 2013. During the 1960s, the average annual catch of sailfish in the western Atlantic Ocean was about 616 t followed by a rapid increase trend when the average annual catch reached about 883 t in 1970s, 1058 t in 1980s and 1199 t in 1990s. After 2009, in the last 5 years of the time series (2010-2014), the average annual catch decreased abruptly and reached a level of 751 t (**Figure 1**).

Model fits to catch-per-unit-effort indices

The predicted CPUE indices from model fit were compared to the observed CPUE. The predicted CPUE of recreational fisheries of USA (1 and 2) and drift gillnet fisheries of Venezuela fluctuated around the observed CPUE time series (**Figure 4**). However, the model fits to the western Atlantic sailfish CPUEs indicated that there was a lack of fit from longline fisheries of Japan, United States, Brazil and Venezuela and also from Brazilian and Venezuelan recreational fisheries (**Figure 4**).

Convergence of model

The autocorrelation function plot indicated a thinning interval of 100 which was large enough to address potential autocorrelation in the MCMC runs. The visual inspection of trace plots of the major parameters showed the good mixing of the three chains (i.e., moving around the parameter space), also indicative of convergence of the MCMC chains. The Gelman and Rubin statistic for all parameters, including all variance terms, equaled 1, which indicated convergence of the Markov chains. Similarly, the Heidelberger and Welch test could not reject the hypothesis that the MCMC chains were stationary at the 95% confidence level for any of the parameters. Overall, these diagnostics indicated that the posterior distribution of the model parameters was adequately sampled with the MCMC simulations (see **Appendix A** for details).

Posterior correlation

Posterior estimates of r, K, and MSY were examined for correlations. For the major model parameters, the joint posterior for r and K has a “banana” type appearance indicating the typical strong correlation between r and K (**Figures 5**). On the other hand, the joint posterior for r and MSY has a “fried-egg” appearance with no correlation eminent. Strong correlation was also observed in the joint posterior of MSY and K (**Figure 5**).

Posterior estimates of model parameters

Plots of posterior densities together with prior densities are depicted in **Figure 6**. Summaries of posterior quantiles of parameters and quantities of management interest were provided in **Table 1**. The marginal posterior for r has a median of about 0.13 (0.08 - 0.20; 95% C.I.) lower than the prior. The posterior for K has a median of 40,173 metric tons (25,190 – 79,031 95% C.I.). The marginal posteriors for MSY, H_{MSY}, and B_{MSY} were centered at the median values of 1,316 metric tons, 0.06, and 20,086 metric tons.

The exploitable biomass of western Atlantic sailfish has decreased until middle of 1980s followed by an increasing trend until 2014 (**Figure 7**). The harvest rate fluctuated for much longer below of H_{MSY} over the period 1961-1980 followed by a stable trend slightly below of H_{MSY} from beginning of 1980s (**Figure 7**). However, the harvest rate has increased to above H_{MSY} in the beginning of 2000s followed by a strong declining pattern until the final of the model time-series (**Figure 7**).

During of the assessment time horizon of 1961-2014, kobe phase plots showed that the western Atlantic sailfish stock appear to be no overfished and no overfishing is occurring (green phase) except in the middle of 1980s in relation to B/B_{MSY} (yellow phase) and in the beginning of 2000s regarding to H/H_{MSY} (orange phase) (**Figure 8**).

Discussion

The results of this study suggest that the western Atlantic sailfish population biomass has slightly declined over the available time series but has remained stable since middle 1980s. Analyses also showed that is very likely that western Atlantic sailfish stock biomass was above of B_{MSY} in 2014. In addition, it is very unlikely that western Atlantic sailfish population was being fished in excess of its optimal equilibrium harvest rate in 2014. In general, the harvest rate has followed the western Atlantic sailfish catches pattern. After the increasing trend of sailfish catches over the period 1961-2000, when the harvest rates increased to above $H_{\text{MSY},}$ sailfish catches showed a declining pattern, and harvest rates also declined to around 50% of H_{MSY} in the last year of the model-frame.

However, it is important to highlight that there is an uncertainty in estimated quantities of stock biomass as well as the estimated harvest rates, since that 95% credibility intervals are somewhat high. Furthermore, inspection of smoothed trends of the individual CPUE indices indicates differences in trend patterns amongst the time series which result in a high uncertainty with respect to the current trajectory of this stock. Larger indices and variability observed for some CPUEs time-series were poorly fitted by the model. Sensitivity analysis for alternative models which includes different data weighting for each CPUE time series may be further modified in order to improve the model fits. Also the inclusion/exclusion of some CPUE time series might be an option to improve the model fitting. Finally, other variations should be tested including different assumptions, such as the condition of the stock in 1961 (i.e. $P_1=B_{1961}/K$).

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Table 1. Summary of posterior quantiles of parameters for the Bayesian state-space surplus production model for the sailfish in the western Atlantic Ocean.

	2.5%	***Median***	***97.5%***
R	0.086	0.132	0.201
K	25,190	40,173	79,031
MSY	0.971	1.316	2.268
H_{MSY}	0.043	0.066	0.101
B_{MSY}	12,595	20,086	39,515
$B_{2014}/B_{\mathrm{MSY}}$	1.017	1.333	1.699
$H_{2014}/H_{\mathrm{MSY}}$	0.186	0.382	0.606

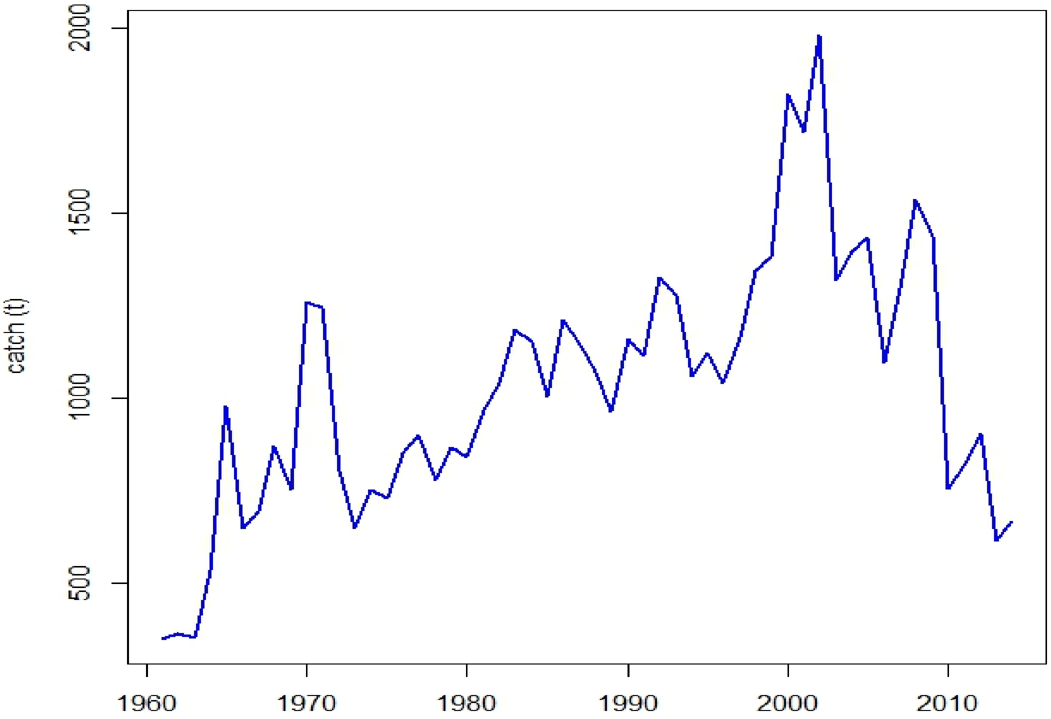

Figure 1. Time-series of catch (t) for the sailfish in the western Atlantic Ocean.

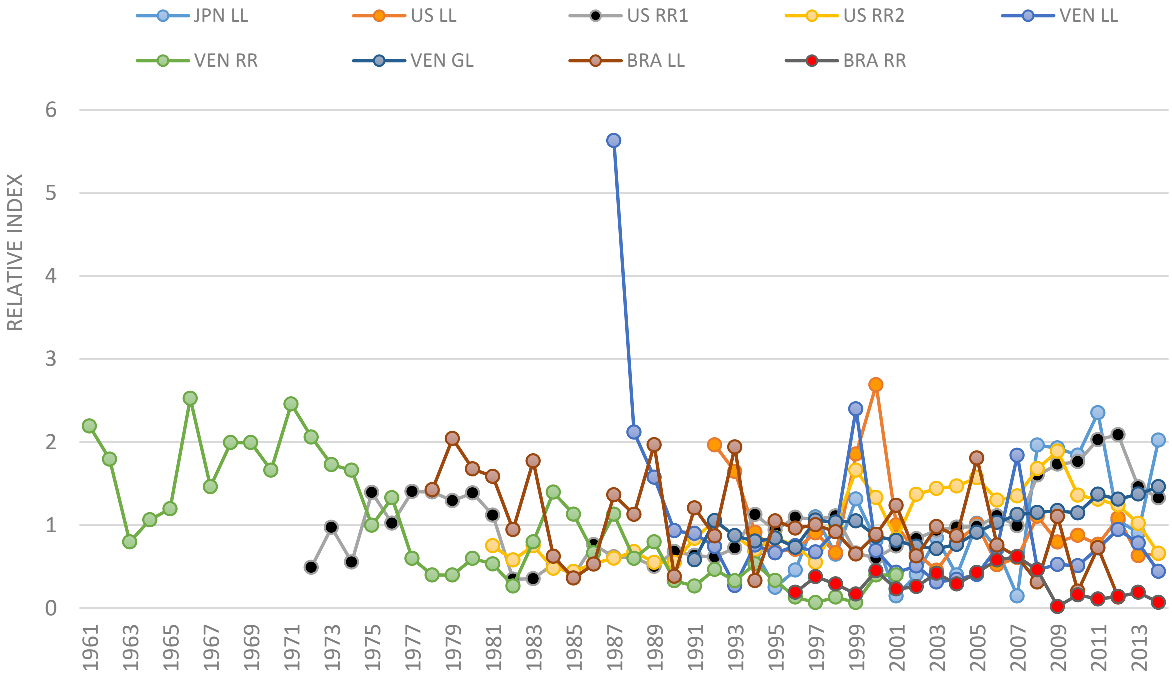

Figure 2. Time-series of nine standardized CPUE series for the sailfish in the western Atlantic Ocean

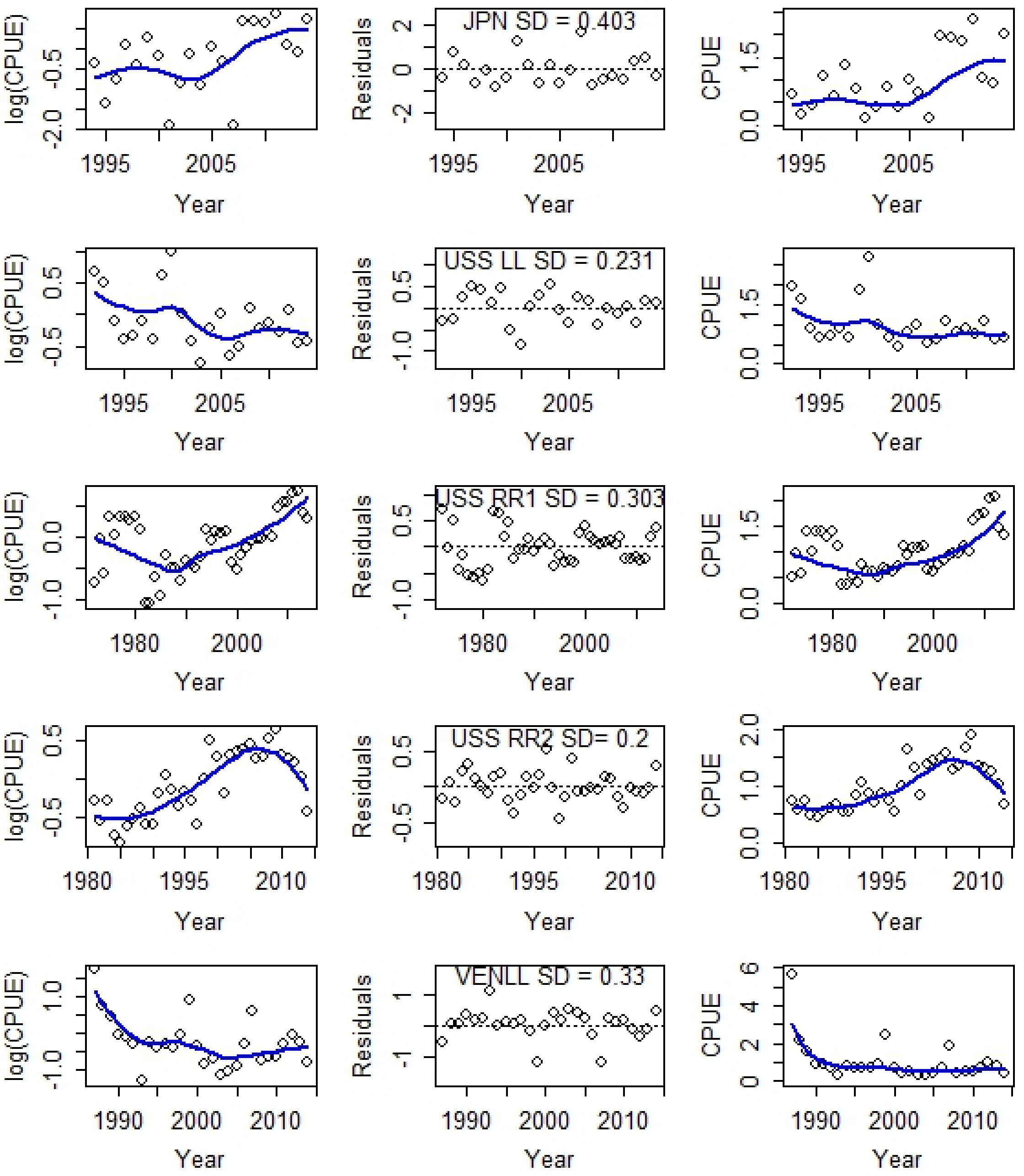

Figure 3. Loess smoother fits used to estimate CV's for CPUE series as input for the assessments (c.f. Francis 2011). Left panel: Smoother fits to log(CPUE) data; Middle panel: Residual plots and estimated CV's for each times series. Right panel: Loess smoother fits illustrated for CPUE indices.

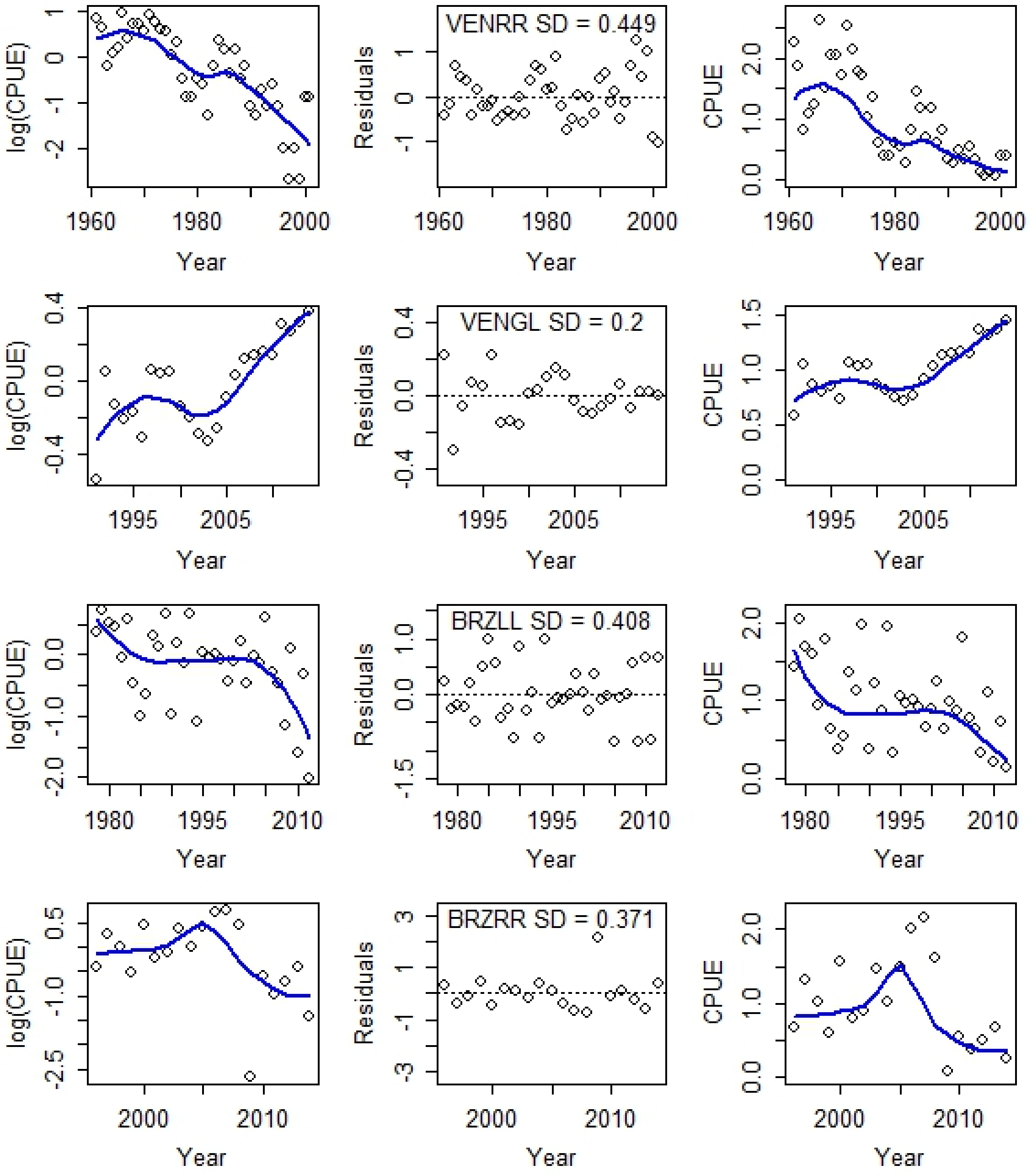

Figure 3. continuation

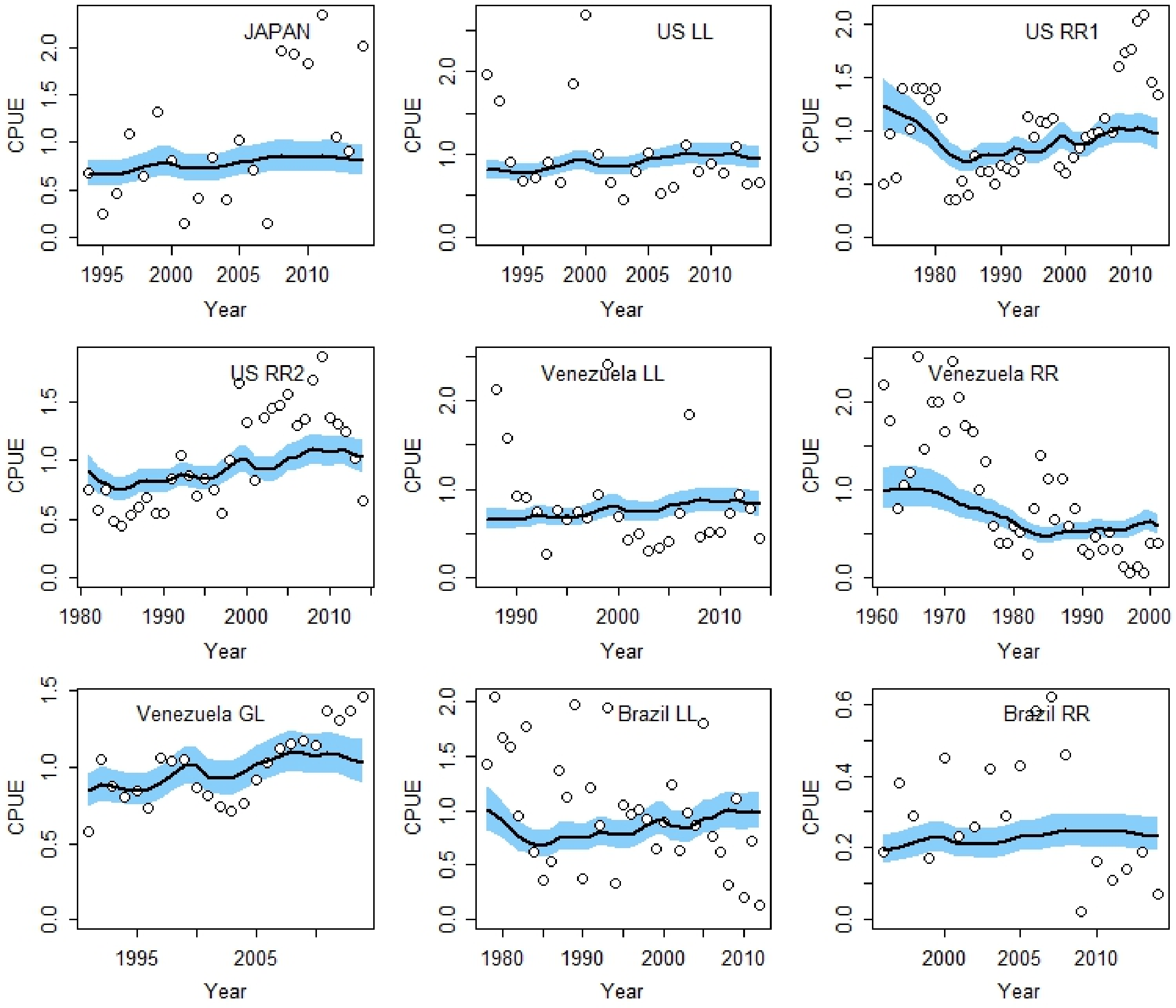

Figure 4. Time-series of observed (circle) and predicted (solid line) catch per unit effort (CPUE) of sailfish in the western Atlantic Ocean for the Bayesian state-space surplus production model. Shaded blue area indicates 95% C.I.

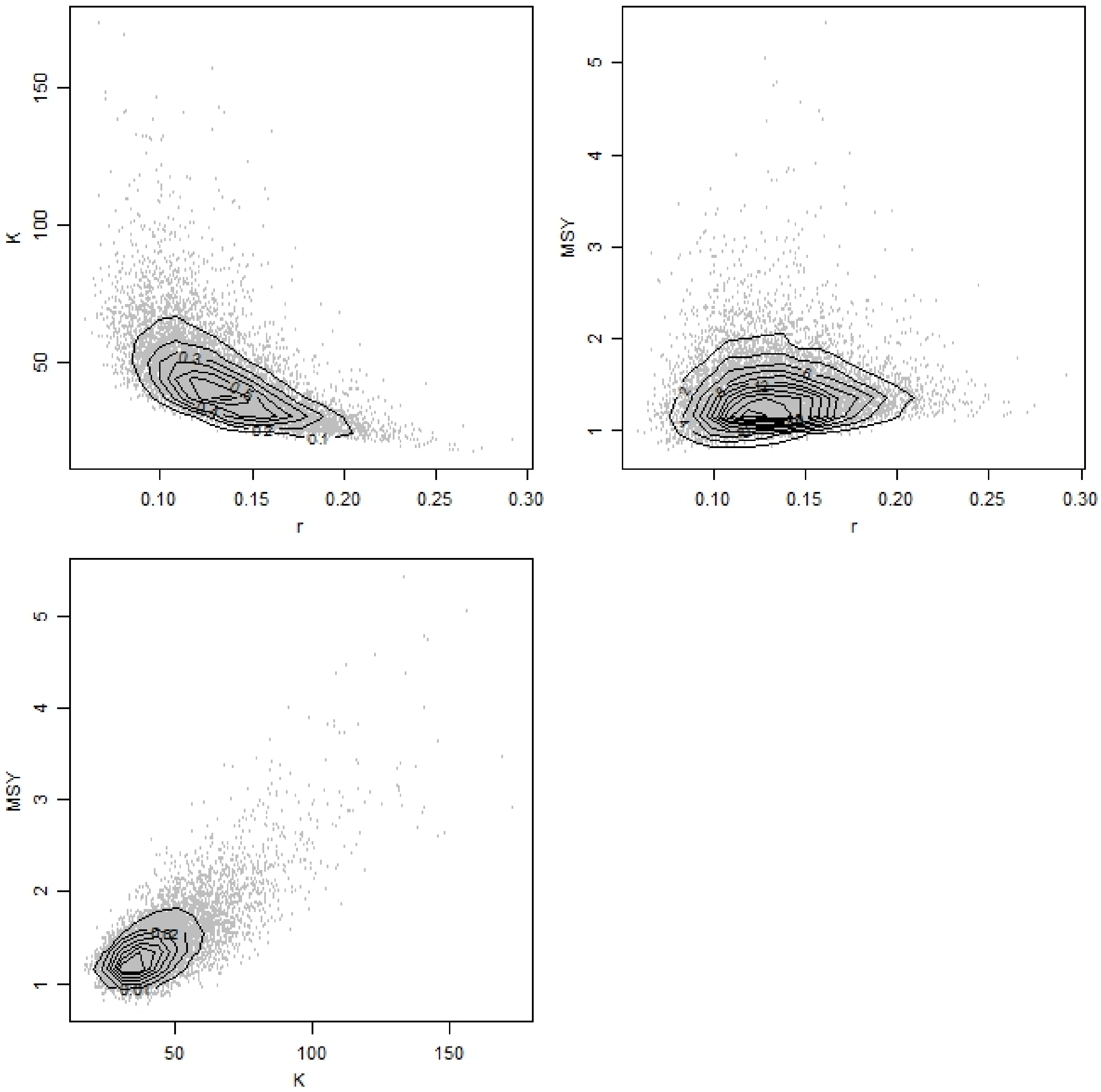

Figure 5. Joint-posterior plots of main model parameters for the Bayesian state-space surplus production model for the sailfish in the western Atlantic Ocean.

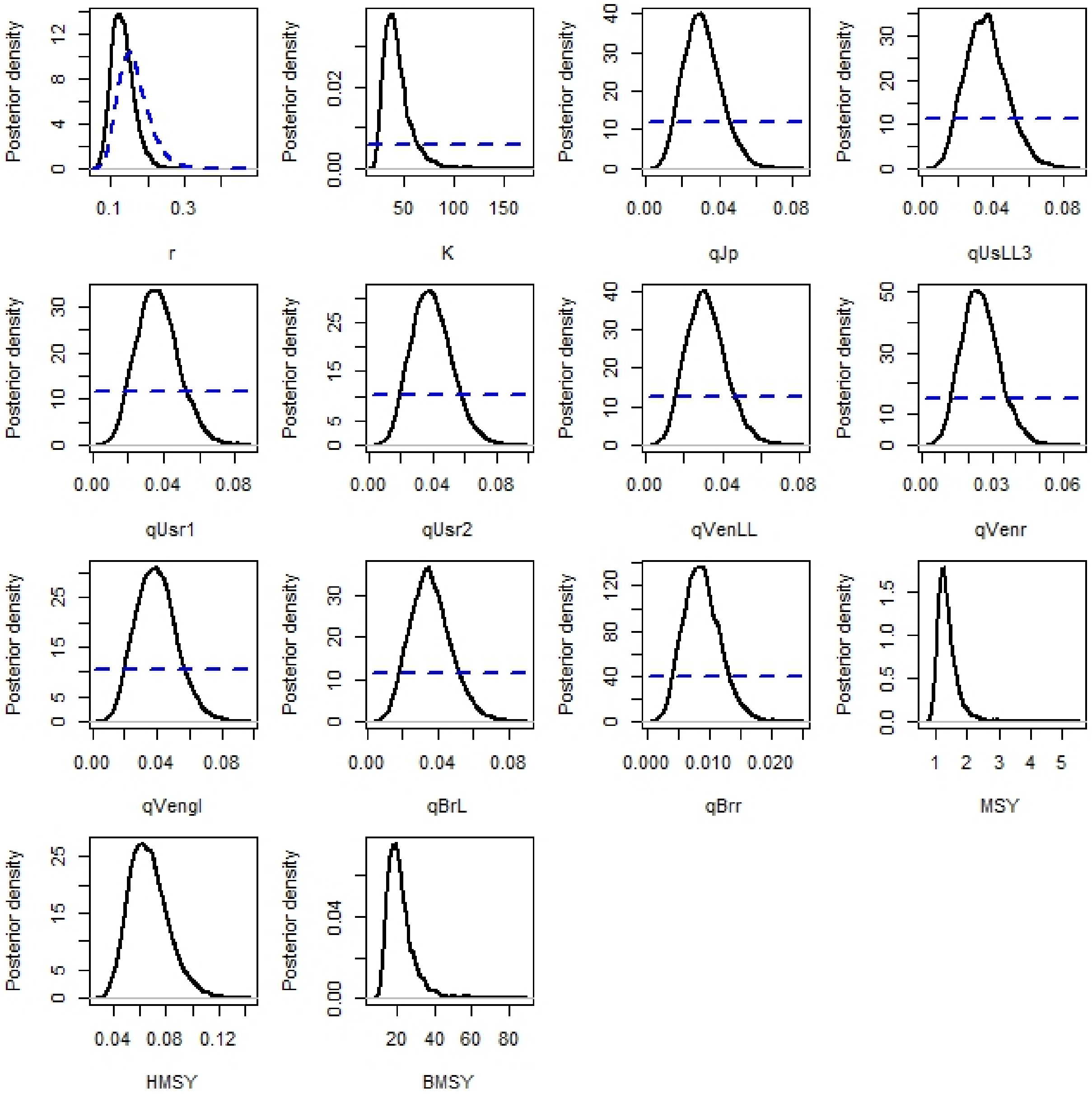

Figure 6. Kernel density estimates (black lines) of the posterior distribution of various model and management parameters for the Bayesian state-space surplus production model for the sailfish in the western Atlantic Ocean. Prior densities are given by the blue dashed lines.

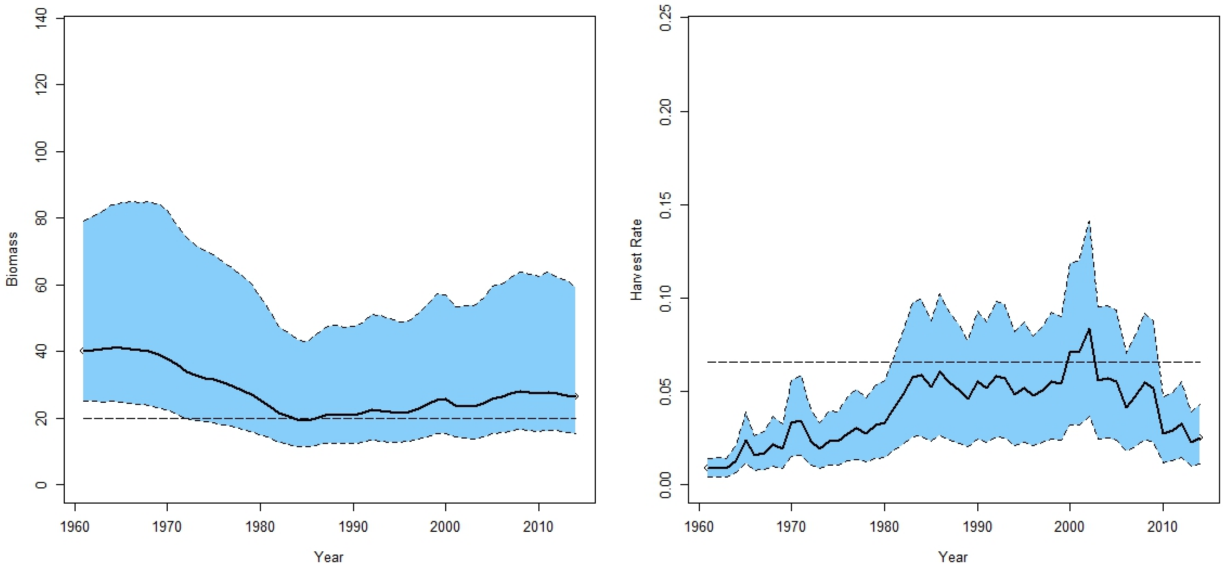

Figure 7. Trends in exploitable biomass (in 1000s metric ton) and harvest rate for the Bayesian state-space surplus production model for the western Atlantic sailfish. Shaded blue area indicates 95% C.I. The horizontal dashed lines denote the B_{MSY} and H_{MSY}.

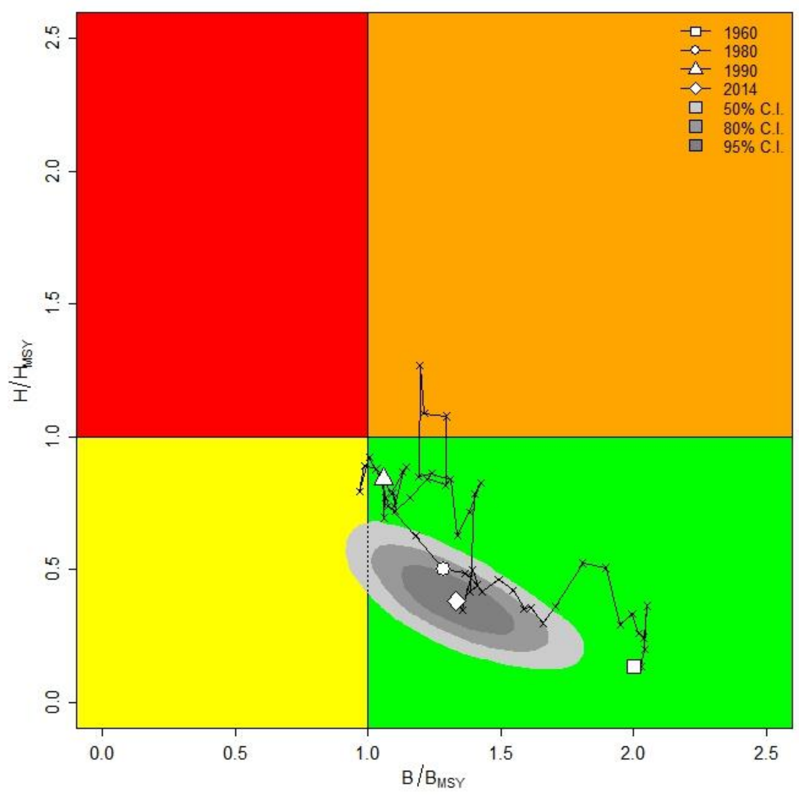

Figure 8. Kobe diagram showing the estimated trajectories (1961-2014) of B/B_{MSY} and H/H_{MSY} for the Bayesian state-space surplus production model for the western Atlantic sailfish.

Appendix A

Tables and figures of model results

Table A1. Heidelberger and Welch's (1983) stationarity and half-width tests for the model parameters.

Node	Stationarity test			Halfwidth test		
	Start iteration	*P*-value	Passed?	Mean	Halfwidth	Passed?
K	1	0.982	Yes	43.12792	1.008303	Yes
r	1	0.926	Yes	0.1347	0.001192	Yes
qJp	1	0.988	Yes	0.03107	0.000627	Yes
qUsLL	1	0.998	Yes	0.03662	0.000738	Yes
qUSr1	1	0.996	Yes	0.03713	0.000752	Yes
qUSr2	1	0.995	Yes	0.03972	0.000817	Yes
qVenLL	1	0.997	Yes	0.03193	0.000656	Yes
qVenr	1	0.997	Yes	0.02531	0.000495	Yes
qVengl	1	0.998	Yes	0.03984	0.000822	Yes
qBrL	1	0.998	Yes	0.03625	0.000747	Yes
qBrr	1	0.999	Yes	0.00902	0.000186	Yes

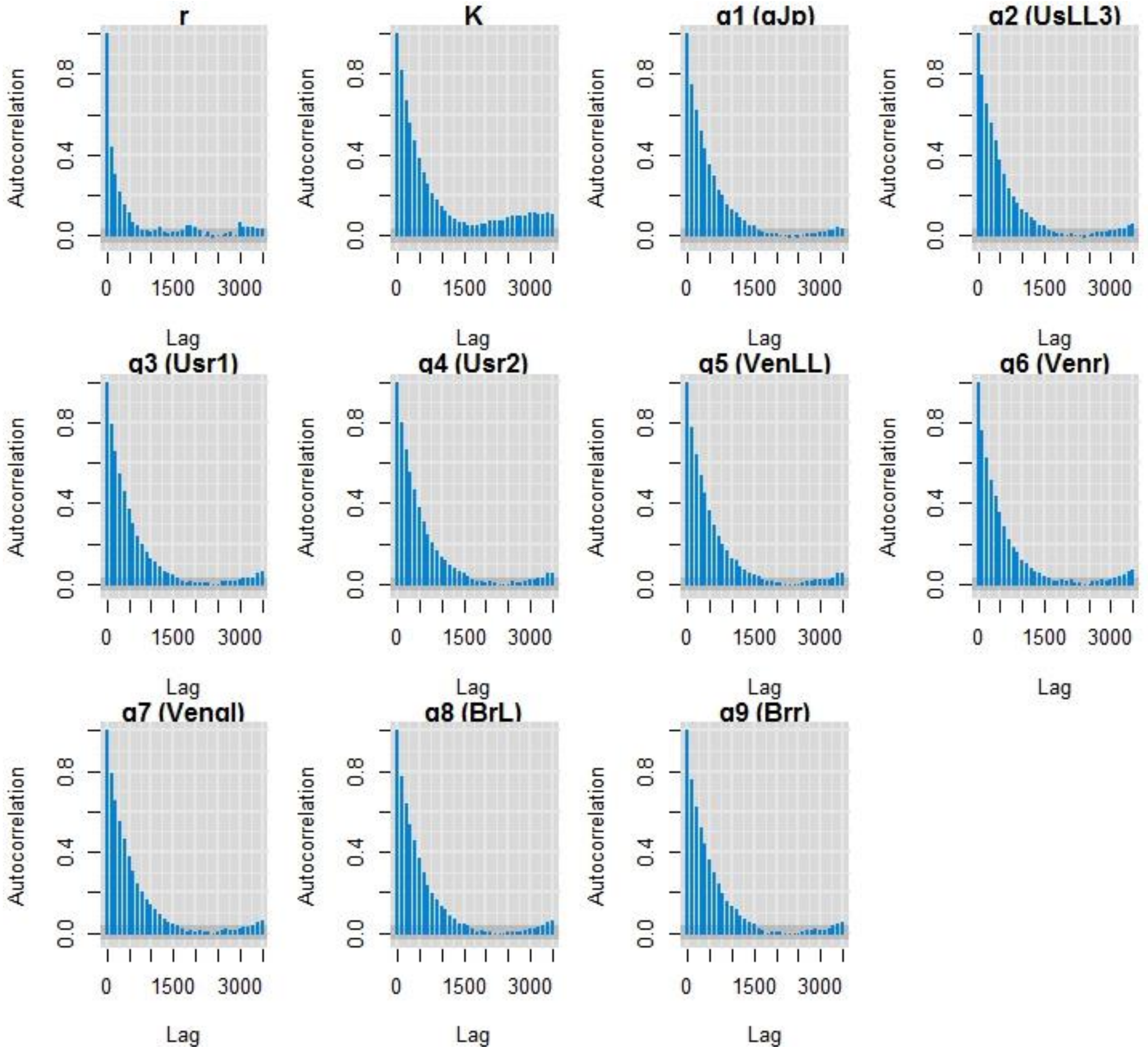

Figure A1. Autocorrelation function plots of main model parameters for Bayesian state-surplus production model for the western Atlantic sailfish. Three chains showed highly coherent autocorrelation plots.

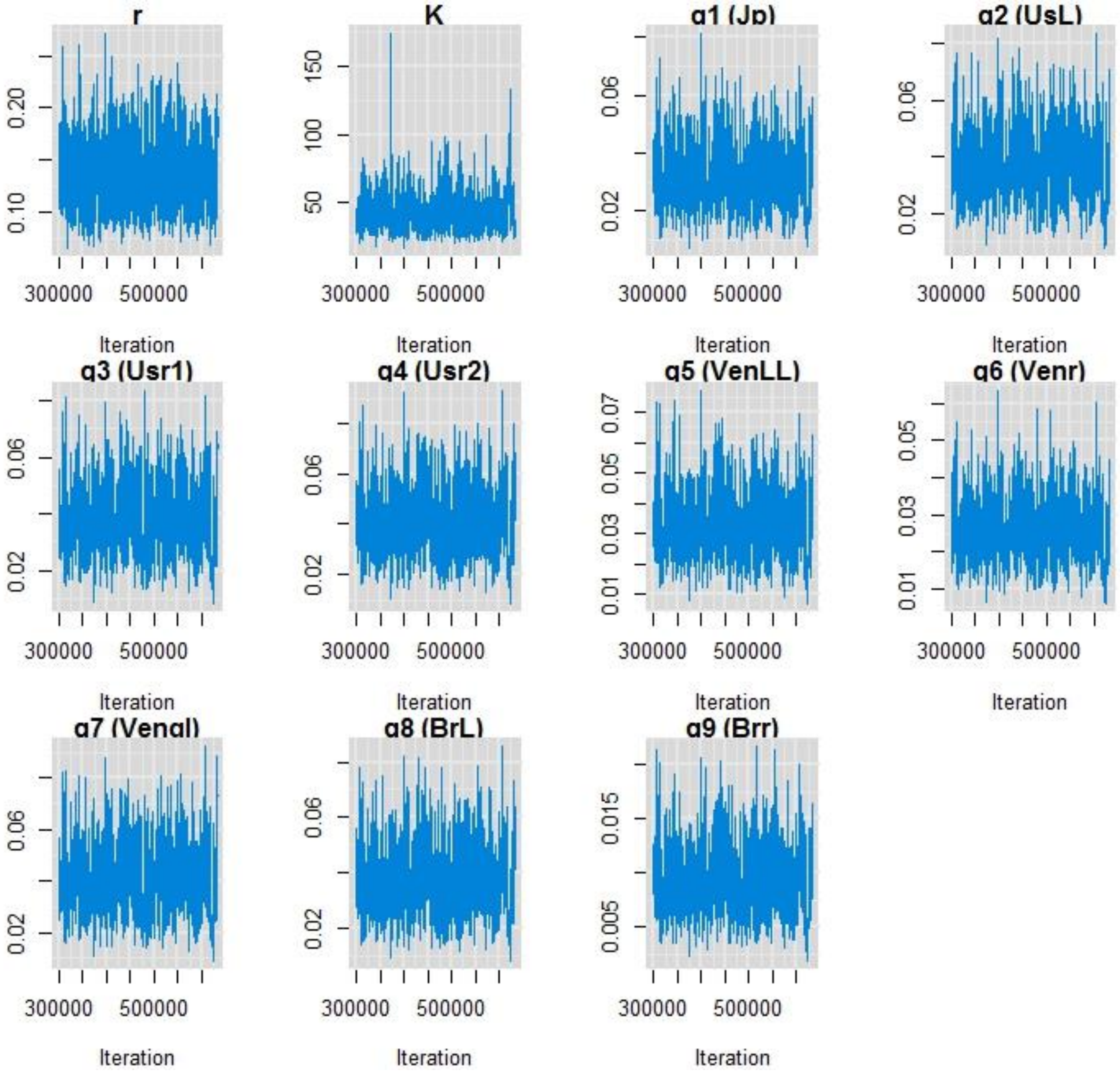

Figure A2. Trace plots for the main model parameter drawn from MCMC samples in the Bayesian state-surplus production model for the western Atlantic sailfish.