Received: 13 July 2014

Analyzing population dynamics of Indian Ocean albacore (*Thunnus alalunga*) using Bayesian biomass dynamics model

Wenjiang Guan, Jiangfeng Zhu, Liuxiong Xu

College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China; Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources, Ministry of Education, Shanghai Ocean University, Shanghai 201306, China

Abstract: Two continuous biomass dynamics models (i.e. Logistic-form and Fox-form biomass dynamics models) were developed based on WinBUGS to assess the stock status of Indian Ocean albacore (*Thunnus alalunga*) using 33 years of fishery data (1980-2012). The results showed that for the Logistic-form biomass dynamics model, the mean of Maximum sustainable yield (MSY) was estimated to be 32798 t, and the mean of B_{2012}/B_{MSY} and F_{2012}/F_{MSY} was 0.93 and 1.18, respectively. For the Fox-form biomass dynamics model, the mean of MSY was 35796 t, and the mean of B_{2012}/B_{MSY} and F_{2012}/F_{MSY} was 1.17 and 0.84, respectively. The risk assessments suggested that for the Fox-form biomass dynamics model, the current catch level in 2012 (33864 t) was lower than MSY (mean value) and this level can introduce lower risk for the fishery to exceed F_{MSY} and B_{MSY}. However, for Logistic-form biomass dynamics model, the result was more pessimistic, i.e., the current catch level was higher than MSY (mean value) and this level can introduce higher risk for the fishery to exceed F_{MSY} and B_{MSY}. There were high uncertainties in both models; however, the Fox-form biomass dynamics model was fitted little better than the Logistic-form model.

1 Introduction

The stock status of Indian Ocean albacore (*Thunnus alalunga*) (ALB) was assessed based on ASPIC (Nishida and Matsumoto, 2011; Matsumoto et al, 2012), ASPM (Nishida et al, 2012) and SS3 (Kitakado et al., 2012). However, there are a lot of uncertainties in catch at age or size data (IOTC, 2013), biological and ecological parameters (Nishida et al., 2014), and key model parameters which must be fixed in complex models, e.g. steepness and recruitment deviation (Kitakado et al., 2012). In this study, we chose simple and highly aggregated model, i.e., biomass dynamics model to assess the ALB stock in order to avoid using lots of biological parameters which were considered to be uncertain. Instead of using the traditional ASPIC model, we developed a continuous biomass dynamics model using Bayesian methods based on winBUGS platform to provide an opportunity to compare results with other stock assessment models.

2 Input data

2.1 Catch Data

The catch data was from the file IOTC-2014-WPTmT-DATA-SA.xlsx which was provided by the IOTC secretariat and downloaded from the IOTC website (http://www.iotc.org/meetings/5th-working-party-temperate-tunas). The Fig. 1 showed the catch by gear from 1950 to 2012.

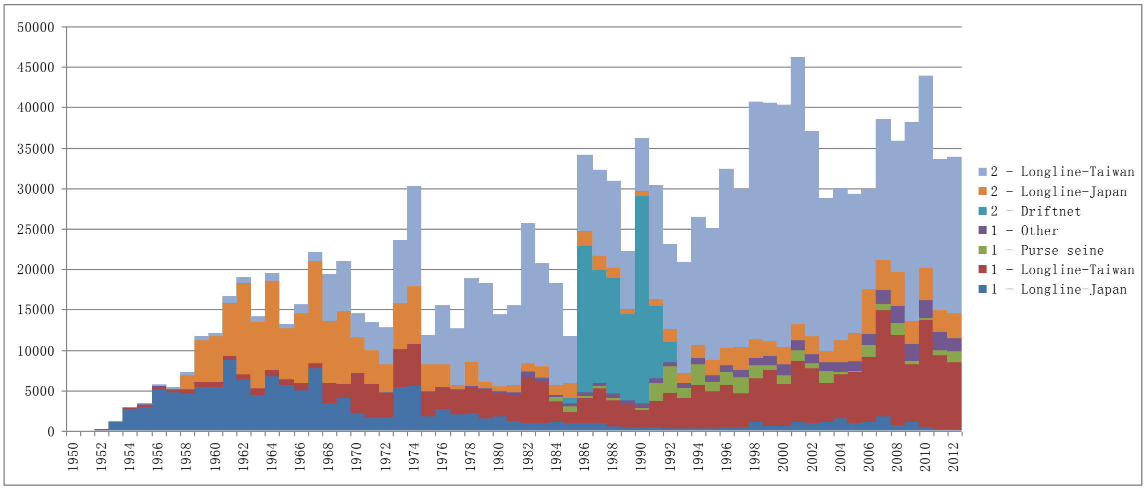

Fig. 1 Historical catch (t) of albacore by gear (IOTC secretarial, 2014)

2.2 CPUE Data

The IOTC website provided two standardized CPUE time series from Japan longline fishery (Matsumoto et al., 2014) and Taiwan, China loneline fishery (Lee et al.,2014). Only the standardized CPUE for all area from 1980 to 2012 from Taiwan, China longline fishery was used in our model. Other CPUE indices were not used because of inconsistence in spatial scales. Fig. 2 showed the CPUE index time series.

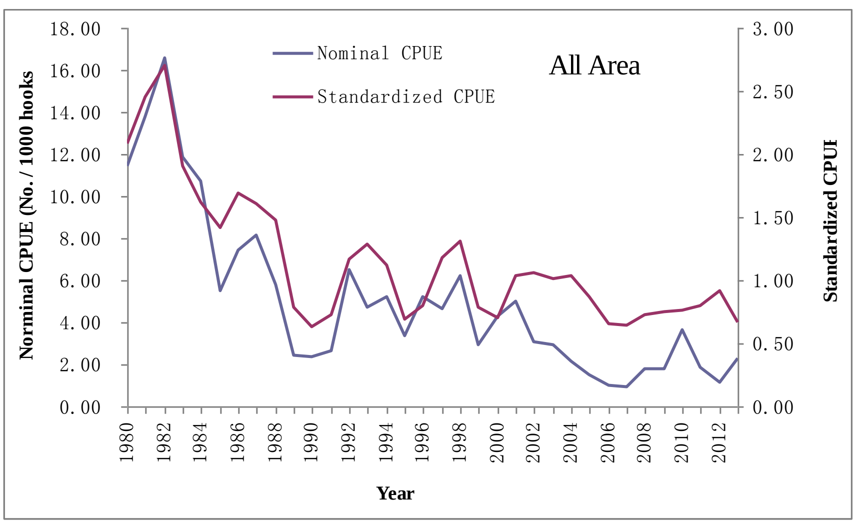

Fig. 2 CPUE series from Taiwan, China longline fishery (IOTC secretarial, 2014)

3 Continuous biomass dynamics models

3.1 Differential equations for biomass dynamics models

The differential equation describing the rate of change of stock biomass due to production and fishing mortality can be written as:

$$\frac{dB_t}{dt} = f(B_t) - F_t B_t \quad (1)$$

where B_t and F_t represents stock biomass and fishing mortality at time *t*, respectively. For Logistic-form biomass dynamics model, the function $f(B_t)$ is (Haddon, 2001):

$$f(B_t) = rB_t(1 - \frac{B_t}{K}) \quad (2)$$

where r represents the intrinsic rate of increase and K represents the maximum population size or carrying capacity.
For Fox-form biomass dynamics model, the function $f(B_t)$ is (Haddon, 2001):

$$f(B_t) = rB_t(\ln(K) - \ln(B_t)) \quad (3)$$

3.2 Continuous Logistic-form biomass dynamics model:

If F_t is constant from time t to $t+\Delta t$, according to Prager (1994), the equations for continuous Logistic-form biomass dynamics model were as follows:

$$B_{t+\Delta t} = \frac{\alpha_t B_t e^{\alpha_t \Delta t}}{\alpha_t + \beta B_t (e^{\alpha_t \Delta t} - 1)} \qquad a_t \neq 0 \quad (4)$$

$$B_{t+\Delta t} = \frac{B_t}{1 + \beta \Delta t B_t} \qquad a_t = 0 \quad (5)$$

$$F_t = \frac{Y_t}{\beta} \ln(1 - \frac{\beta B_t (1 - e^{\alpha_t \Delta t})}{\alpha_t}) \qquad a_t \neq 0 \quad (6)$$

$$F_t = \frac{Y_t}{\beta} \ln(1 + \beta \Delta t B_t) \qquad a_t = 0 \quad (7)$$

$$\beta = r / K \quad (8)$$

$$\alpha_t = r - F_t \quad (9)$$

where Y_t represents yield during from t to $t+\Delta t$.

3.3 Continuous Fox-form biomass dynamics model

If F_t is constant from time t to $t+\Delta t$, the equations for continuous Fox-form biomass dynamics model were as follows:

$$B_{t+\Delta t} = e^{(A - e^{-r\Delta t}(A - r\ln(B_t)))/r} \quad (10)$$

$$A = r\ln(K) - F_t \quad (11)$$

$$F_t = \frac{\int_0^{\Delta t} B_{t+x} dx}{Y_t} \quad (12)$$

In our models, time unit is one year, so Δt is 1.0.

3.4 The likelihood function

We assumed log-normal distribution for CPUE time series, so the likelihood function can be written as:

$$L(data \mid B_{1980}/B_{1950}, r, K, q, \sigma) = \prod_t \frac{1}{I_t \sigma \sqrt{2\pi}} e^{-\frac{(\ln(I_t) - \ln(\hat{I}_t))^2}{2\sigma^2}} \quad (13)$$

$$\hat{I}_t = q\overline{B}_t \quad (14)$$

$$\overline{B}_t = \frac{Y_t}{F_t} \quad (15)$$

where q is catchablity and I_t is CPUE time series. $B_{1980/1950}$ represents B_{1980} or B_{1950}, according to which data was used. The source codes for the two models are given in Appendix B.

4 Model run

4.1 Re-parameterization and scale the data

For biomass dynamics models, there are five parameters to be estimated, i.e., r, K, $B_{1980/1950}$, q, and σ. For better computational stability, we re-parameterized the $B_{1980/1950}$ as B_0 using equation (16), and scale the catch and CPUE by maximum of the catch or CPUE time series using equation (17) and (18).

$$B_{1980/1950}=B_0 \text{ K} \quad (16)$$

$$Y_t = \frac{Y_t}{Y_{Max}} \quad (17)$$

$$I_t = \frac{CPUE_t}{CPUE_{Max}} \quad (18)$$

4.2 Prior for parameters

We assigned priors for q as a uniform distribution between 0.0 and 1.0, because we have no clear information. We also have no information for $\tau=1/\sigma^2$, so a non-information prior was assigned for τ as Gamma distribution (Gamma(0.001, 0.001)). According to recent stock assessment, we guessed K would be 4 times larger than maximum catch, but we did not know the upper limit of K exactly and B_0 should be larger than 0.1 and the upper limit of B_0 should be 1.0. We set the upper limit for K as 50 times of maximum catch. Therefore, two uniform distributions were assigned for K (Unif (4, 50)) and for B_0 (Unif (0.1, 1.0)). According Hillary (2008), the mean and CV of intrinsic rate of increase for Indian Ocean albacore were 0.43 and 0.14, respectively. So a log-normal distribution with mean 0.43 and variance 0.0194 (log(0.14*0.14+1)) was assigned for parameter r.

4.3 Sensitivity run

We added two scenarios where the lower limit of K was set as 3 and six scenarios where the distribution of r was assigned as uniform distribution with different lower limits of r (Table 1).

Two catch time series, i.e. 1950 to 2012 and 1980 to 2012 were used for analysis.

Table 1 Prior for each parameter

Scenario	Model	Data	r	K	q	B_0	$\tau=1/\sigma^2$
1	Logistic	1980-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
2	Logistic	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
3	Logistic	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.9,1.0)	Gamma(0.001,0.001)
4	Logistic	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.8,0.9)	Gamma(0.001,0.001)
5	Fox	1980-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
6	Fox	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
7	Fox	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.9,1.0)	Gamma(0.001,0.001)
8	Fox	1950-12	Lm(0.43,0.14)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.8,0.9)	Gamma(0.001,0.001)
9	Logistic	1980-12	Lm(0.43,0.14)	Unif(3, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
10	Fox	1980-12	Lm(0.43,0.14)	Unif(3, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
11	Logistic	1980-12	Unif(0.05, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
12	Logistic	1980-12	Unif(0.10, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
13	Logistic	1980-12	Unif(0.25, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
14	Fox	1980-12	Unif(0.05, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
15	Fox	1980-12	Unif(0.10, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)
16	Fox	1980-12	Unif(0.25, 2.0)	Unif(4, 50)	Unif(0, 1.0)	Unif(0.1,1.0)	Gamma(0.001,0.001)

Lm: denote log-normal distribution mean=log(0.43), sd=0.14

5 Results and discussion

According to Gelman and Rubin's convergence diagnostic, all scenarios except scenario 9 seemed to be converged (Appendix A showed the diagnostic for scenario 1, 5 and 10). When catch from 1950 to 2012 was used, there was no information in data to estimate B_0 as the posterior distribution of B_0 was also a uniform distribution (Fig 3). Therefore, the B_0 was fixed at small interval for scenario 3, 4, 7 and 8. However, there were no improvements in goodness of fit for the model (Table 2), so the results based on catch from 1950 to 2012 were not analyzed further.

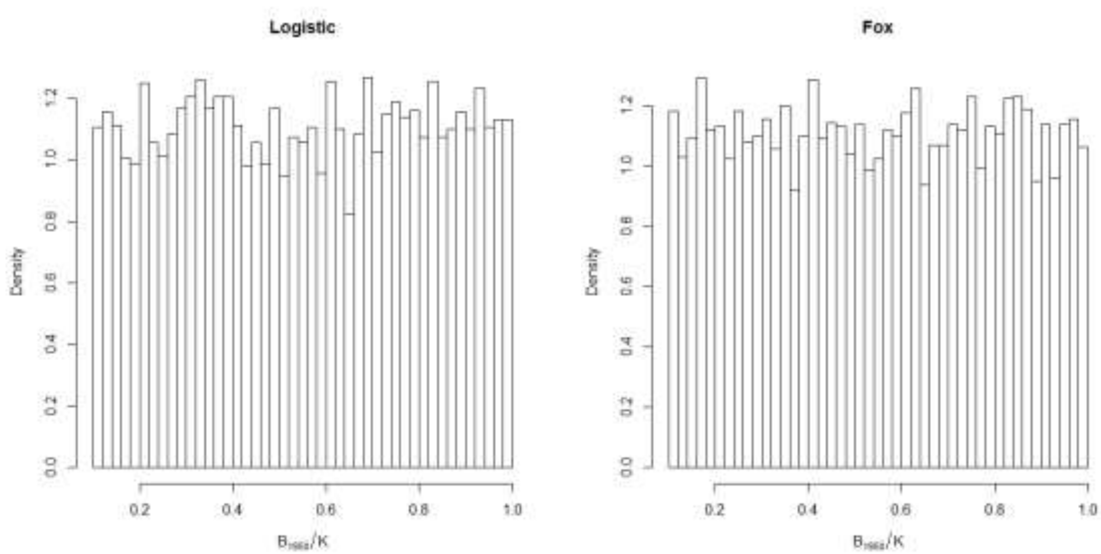

Fig. 3 Distributions of B_0 for scenario 2 and 6, where catch data was from 1950 to 2012 (See Table 1)

The results from Logistic or Fox form biomass dynamics model based on catch from 1980 to 2012 showed that the data can provide information for estimating K, q, and B_0

(Fig. 4 and Fig. 5), but the posterior distribution for *r* was similar as the assigned prior (Fig 4, Fig. 5). As Fig. 5 showed, the lower limit of *K* for scenario 5 seemed a little bit large. The results of scenario 10, where the lower limit of K was set as 3, were similar with scenario 5, but the distribution of *K* was improved (Fig 6, Table 5-8). However, for scenario 9, the model failed to converge.

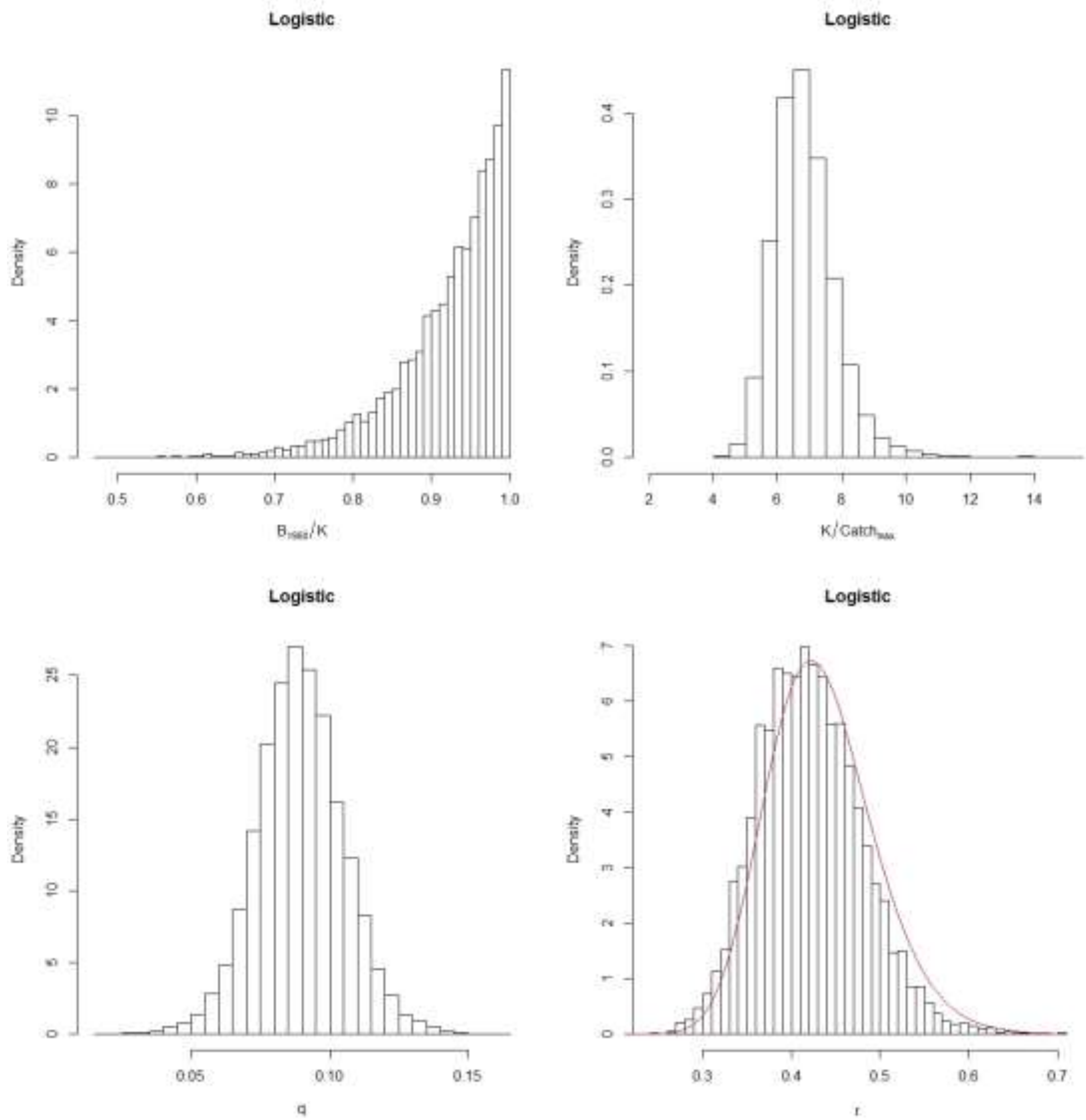

Fig. 4 Posterior distributions for B_0, *K*, *q*, and *r* in scenario 1. The red line is a prior assigned for *r*.

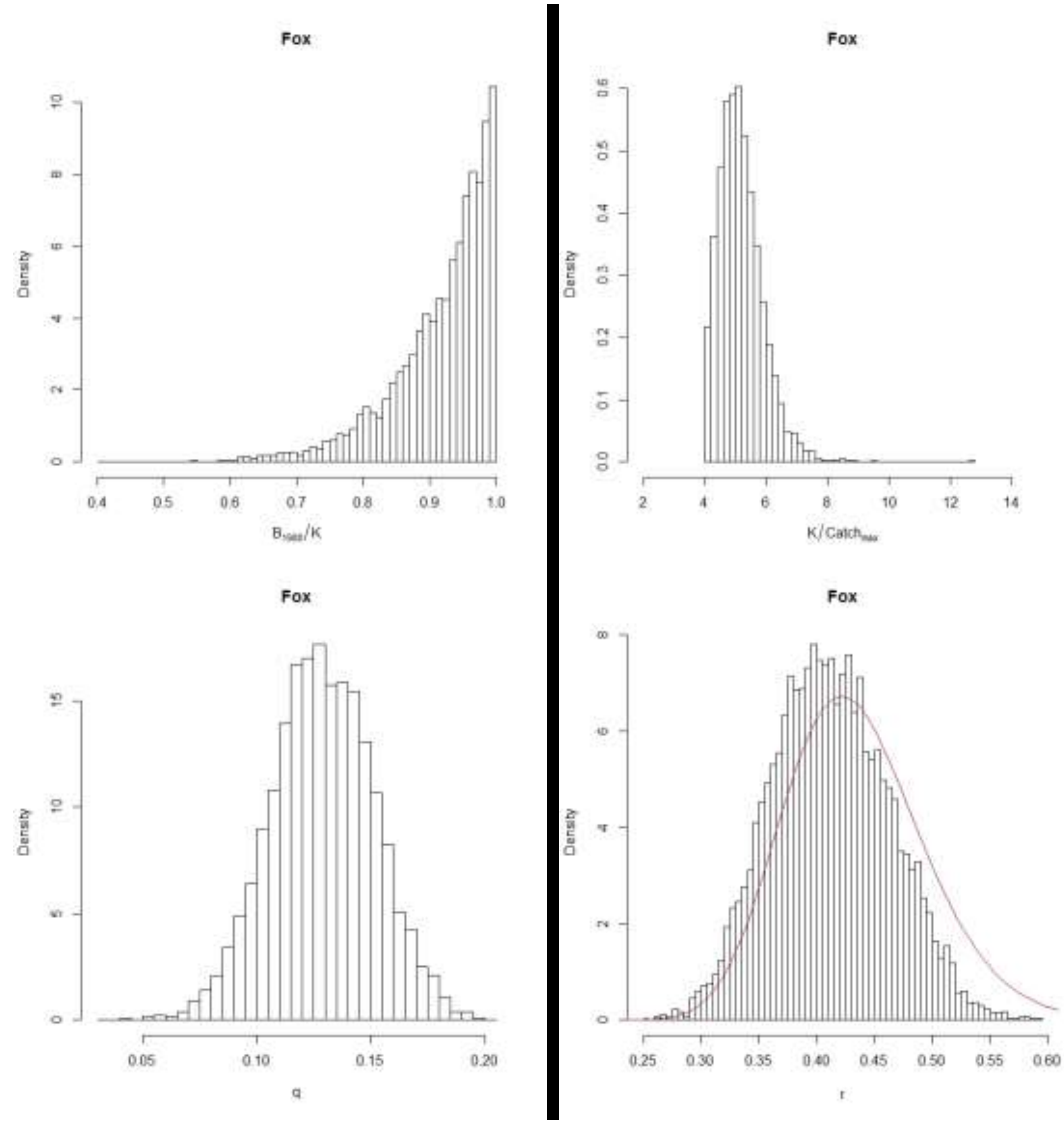

Fig. 5 Posterior distributions for B_0, K, q, and r in scenario 5. The red line is a prior assigned for r.

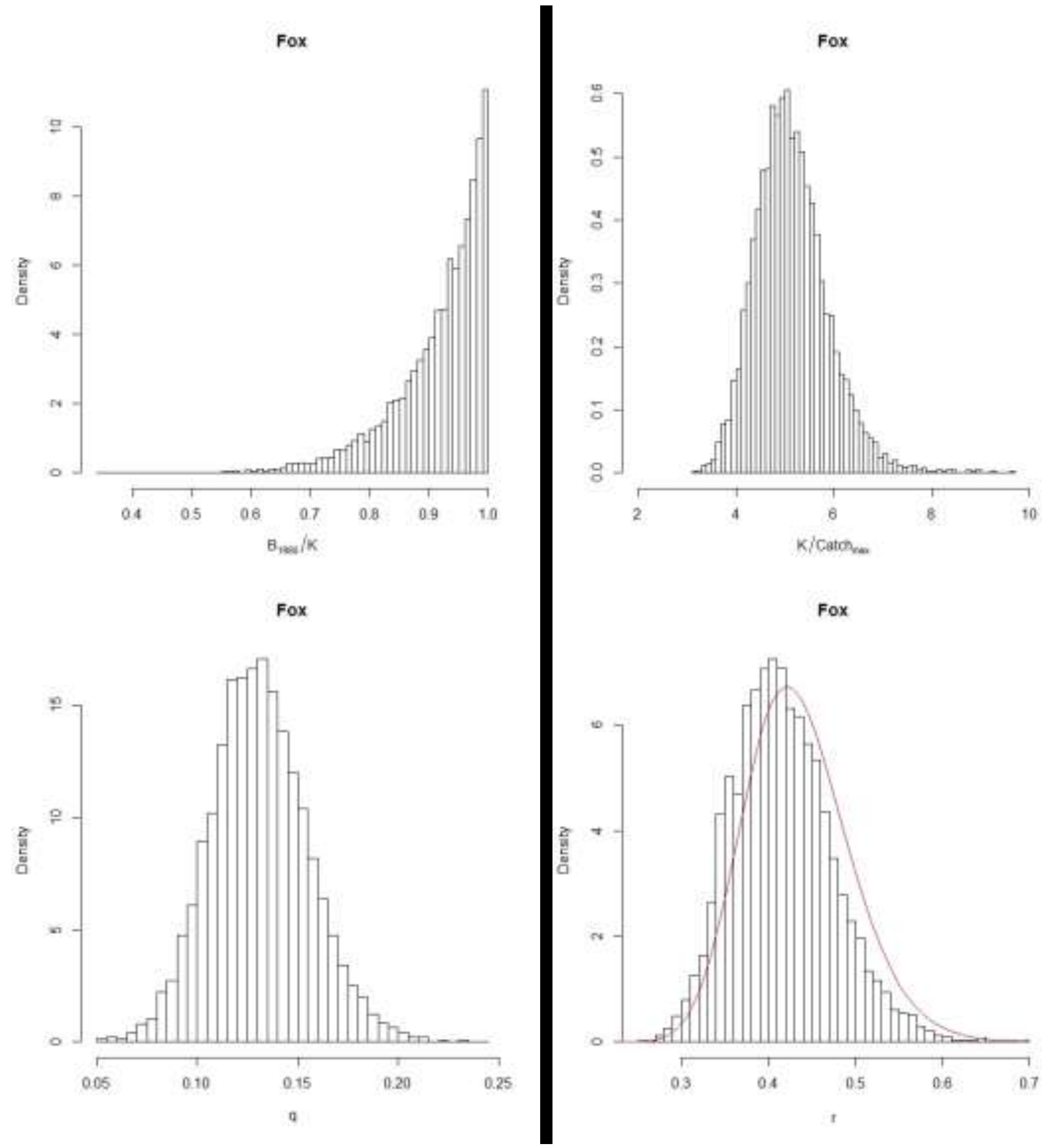

Fig. 6 Posterior distributions for B_0, K, q, and r in scenario 10. The red line is a prior assigned for r.

Table 2 Results for different scenarios in Table 1

Scenario	MSY Mean	K Mean	r Mean	R^2 Mean	MSE Mean	MSY Median	K Median	r Median	R^2 Median	MSE Median
1	32798	316716	0.421	0.537	0.022	32185	311556	0.418	0.549	0.021
2	33556	318673	0.428	0.482	0.024	32324	309150	0.424	0.490	0.024
3	33903	322338	0.427	0.483	0.024	32351	310446	0.422	0.491	0.023
4	33470	318376	0.427	0.482	0.024	32344	309752	0.423	0.490	0.023
5	35900	240099	0.412	0.584	0.019	35201	235530	0.410	0.595	0.019
6	36620	241249	0.418	0.516	0.022	35258	233123	0.417	0.525	0.022
7	36324	238866	0.419	0.516	0.022	35243	232522	0.419	0.523	0.022
8	36692	241643	0.418	0.516	0.022	35291	233077	0.416	0.523	0.022
9	Not converged									
10	35796	237499	0.416	0.583	0.019	35147	234419	0.412	0.594	0.019
11	29570	559694	0.291	0.531	0.022	29400	489106	0.244	0.548	0.021
12	31128	464257	0.328	0.533	0.022	30355	428766	0.283	0.550	0.021
13	34351	327015	0.412	0.530	0.022	32329	317479	0.448	0.549	0.022
14	33073	441498	0.259	0.586	0.019	33014	376130	0.242	0.600	0.019
15	34583	380799	0.283	0.588	0.019	33521	347487	0.267	0.600	0.019
16	36043	274133	0.369	0.588	0.019	34737	270281	0.353	0.596	0.019

For scenarios 11-16, the means or medians of K changed greatly with assumed distributions of r and the K increased when r decreased (Table 2), which maybe meant the information in the data was limited to estimate both r and K simultaneously because the strong correlation between the two parameters. So it is necessary to assign a proper information prior for r or K.

For Logistic-form biomass dynamics model (Scenario 1), the mean of Maximum sustainable yield (MSY) was estimated to be 32798 t, and the mean of B_{2012}/B_{MSY} and F_{2012}/F_{MSY} was 0.93 and 1.18, respectively. For Fox-form biomass dynamics model (Scenario 10), the mean of MSY was 35796 t, and the mean of B_{2012}/B_{MSY} and F_{2012}/F_{MSY} was 1.17 and 0.84, respectively. The Logistic-form biomass dynamics model produced more pessimistic stock status than the Fox-form model (Fig 7-8, and Table 3-4, 7-8). For Logistic-form model, the risk matrix indicated that high risk of B or F exceeding B_{MSY} or F_{MSY} in the future would occur if current catch level is kept (Tables 3-4). However for Fox-form model, the current catch seemed to be safer (Table 7-8).

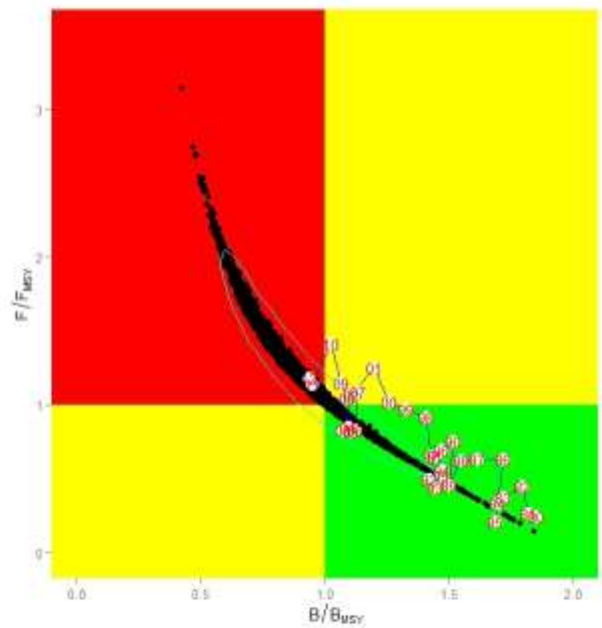

Fig. 7 Kobe plot with 95% confidence surface for scenario 1 (Logistic-form biomass dynamics model)

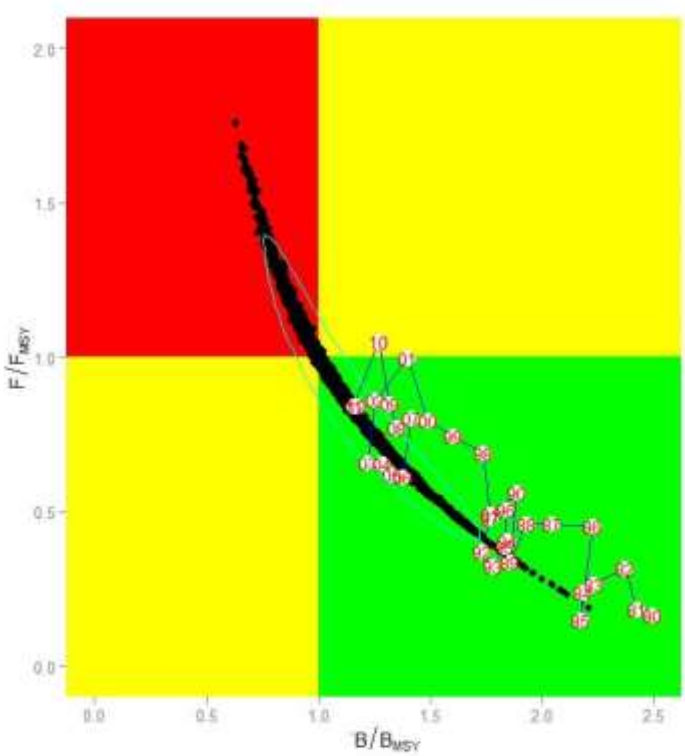

Fig. 8 Kobe plot with 95% confidence surface for scenario 10 (Fox-form biomass dynamics model)

Table 3 Risk matrix for *B*< B_{MSY} for scenario 1 (probability of exceeding B_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0.538	0.384	0.257	0.166	0.103	0.063	0.041	0.030	0.020	0.013	0.01
80%	0.625	0.557	0.496	0.440	0.389	0.349	0.306	0.274	0.250	0.227	0.208
85%	0.646	0.599	0.555	0.516	0.481	0.450	0.420	0.395	0.370	0.352	0.333
90%	0.668	0.638	0.615	0.592	0.571	0.549	0.533	0.517	0.503	0.489	0.478
100%	0.705	0.712	0.718	0.723	0.727	0.731	0.734	0.739	0.743	0.746	0.748
110%	0.738	0.771	0.798	0.82	0.838	0.851	0.863	0.872	0.879	0.885	0.891
120%	0.770	0.824	0.859	0.883	0.901	0.915	0.926	0.935	0.941	0.946	0.95
140%	0.825	0.890	0.929	0.950	0.963	0.971	0.977	0.981	0.983	0.985	0.986

Table 4 Risk matrix for F> F_{MSY} for scenario 1 (probability of exceeding F_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0.060	0.038	0.025	0.016	0.011	0.009	0.007	0.005	0.004	0.004	0.003
80%	0.364	0.326	0.286	0.258	0.236	0.214	0.196	0.18	0.164	0.152	0.141
85%	0.469	0.436	0.409	0.382	0.361	0.345	0.324	0.306	0.292	0.279	0.268
90%	0.565	0.546	0.530	0.514	0.500	0.487	0.476	0.465	0.455	0.446	0.437
100%	0.729	0.733	0.737	0.741	0.745	0.747	0.749	0.751	0.753	0.755	0.756
110%	0.838	0.852	0.863	0.873	0.880	0.887	0.892	0.897	0.903	0.906	0.909
120%	0.904	0.917	0.927	0.935	0.942	0.946	0.95	0.955	0.958	0.961	0.962
140%	0.962	0.971	0.977	0.981	0.983	0.985	0.987	0.987	0.988	0.988	0.989

Table 5 Risk matrix for B< B_{MSY} for scenario 5 (probability of exceeding B_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0.044	0.008	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80%	0.101	0.051	0.026	0.014	0.008	0.004	0.003	0.002	0.002	0.001	0.001
85%	0.120	0.075	0.048	0.031	0.021	0.014	0.011	0.008	0.006	0.004	0.004
90%	0.141	0.107	0.081	0.063	0.051	0.040	0.033	0.028	0.024	0.020	0.019
100%	0.191	0.192	0.193	0.194	0.195	0.195	0.196	0.197	0.198	0.198	0.198
110%	0.245	0.299	0.352	0.402	0.440	0.474	0.507	0.537	0.557	0.577	0.595
120%	0.306	0.431	0.532	0.615	0.680	0.732	0.766	0.791	0.818	0.833	0.849
140%	0.450	0.671	0.800	0.872	0.913	0.936	0.950	0.959	0.966	0.970	0.974

Table 6 Risk matrix for F> F_{MSY} for scenario 5 (probability of exceeding F_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80%	0.024	0.012	0.007	0.004	0.003	0.002	0.001	0.001	0.001	0.000	0.000
85%	0.045	0.03	0.021	0.014	0.009	0.007	0.005	0.004	0.004	0.003	0.003
90%	0.08	0.063	0.049	0.039	0.032	0.028	0.023	0.02	0.018	0.016	0.014
100%	0.194	0.195	0.196	0.197	0.197	0.198	0.199	0.198	0.199	0.199	0.2
110%	0.354	0.402	0.439	0.474	0.508	0.536	0.558	0.577	0.595	0.611	0.626
120%	0.527	0.609	0.676	0.729	0.764	0.792	0.816	0.833	0.847	0.859	0.869
140%	0.787	0.865	0.911	0.934	0.95	0.958	0.965	0.97	0.973	0.976	0.978

Table 7 Risk matrix for B< B_{MSY} for scenario 10 (probability of exceeding B_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0.045	0.009	0.001	0	0	0	0	0	0	0	0
80%	0.102	0.051	0.025	0.014	0.009	0.006	0.003	0.002	0.001	0	0
85%	0.122	0.074	0.047	0.03	0.019	0.014	0.011	0.009	0.007	0.006	0.005
90%	0.144	0.107	0.08	0.065	0.05	0.041	0.032	0.027	0.022	0.019	0.018
100%	0.193	0.193	0.193	0.194	0.195	0.195	0.195	0.196	0.197	0.197	0.198
110%	0.252	0.31	0.364	0.409	0.456	0.49	0.516	0.547	0.574	0.595	0.612
120%	0.321	0.444	0.546	0.632	0.695	0.746	0.782	0.811	0.832	0.851	0.862
140%	0.465	0.685	0.817	0.884	0.92	0.942	0.955	0.963	0.97	0.975	0.978

Table 8 Risk matrix for F> F_{MSY} for scenario 10 (probability of exceeding F_{MSY})

Catch	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
60%	0	0	0	0	0	0	0	0	0	0	0
80%	0.023	0.012	0.008	0.005	0.003	0.002	0	0	0	0	0
85%	0.045	0.028	0.018	0.013	0.01	0.008	0.006	0.005	0.005	0.004	0.003
90%	0.079	0.063	0.049	0.04	0.031	0.026	0.021	0.019	0.017	0.016	0.014
100%	0.195	0.195	0.196	0.196	0.197	0.197	0.197	0.198	0.199	0.2	0.201
110%	0.361	0.409	0.451	0.487	0.516	0.547	0.573	0.595	0.613	0.626	0.639
120%	0.537	0.624	0.69	0.743	0.779	0.809	0.829	0.849	0.861	0.872	0.882
140%	0.803	0.877	0.918	0.941	0.953	0.962	0.97	0.974	0.978	0.981	0.983

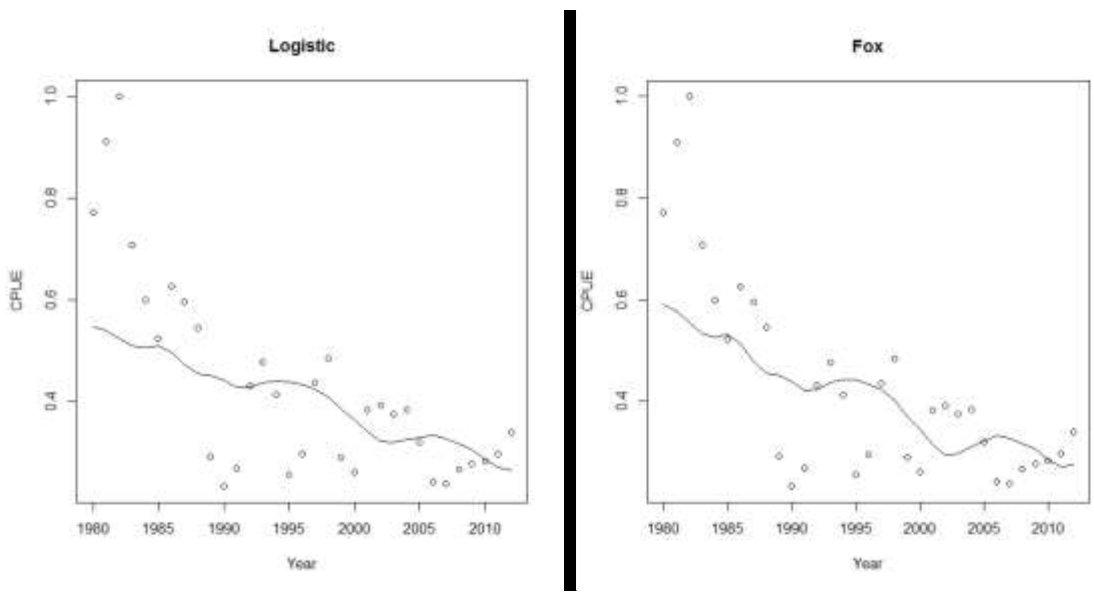

Fig. 9 Observed and predicted CPUE for both models (scenario 1 and 10)

The Fox-form biomass dynamics model was fitted little better than the Logistic-form biomass dynamics model, evaluating with R^2 and MSE (Mean squared error). However, there were high uncertainties in both models (Fig 9).

The available standardized CPUE based on Taiwan, China longline fishery displayed a classical one-way trip and the CPUE can't provide enough information for estimating *r* and *K* simultaneously (Hillary, 2008), because of the strong correlation between the two parameters. The results would be greatly improved in a Bayesian framework if we can gather better knowledge or priors from other studies such as demographic analysis (Carruthers and McAllister, 2011; McAllister et al., 2001).

Acknowledgements

This study was financially supported by Innovation Program of Shanghai Municipal Education Commission (14ZZ147). The study was also supported by National Distant-water Fisheries Engineering Research Center at Shanghai Ocean University (SHOU), Collaborative Innovation Center for Distant-water Fisheries based in SHOU, and International Center for Marine Studies at SHOU.

Reference

Carruthers T., McAllister, M. 2011. Computing prior probability distributions for the intrinsic rate of increase for Atlantic tuna and billfish using demographic methods Collect. Vol. Sci. Pap. ICCAT, 66(5): 2202-2205.

Haddon M. 2001. Modelling and Quantitative Methods in Fisheries. Boca Raton: CRC Press.

Hillary R. M. 2008. Surplus production analyses for Indian Ocean albacore, IOTC-2008-WPTe-06. 10pp.

IOTC. 2012. Report of the Fourth Session of the IOTC Working Party on Temperate Tunas. Shanghai, China, 20–22 August 2012

IOTC. 2013. Report of the sixteen session of the IOTC Scientific Committee. IOTC–2013–SC16–R[E].Busan, Rep. of Korea, 2–6 December 2013.

Kitakado T., Takashima E., Ijima T., *et al*. 2012. First attempt of stock assessment using Stock Synthesis III (SS3) for the Indian Ocean albacore tuna (*Thunnus alalunga*). IOTC–2012–WPTmT04–11 Rev_2. 25pp.

Lee, L. K., Hsu, C. C. and Chang, F.C. 2014. Albacore (*Thunnus alalunga*) CPUE trend from Indian Core Albacore Areas based on Taiwanese longline catch and effort statistics dating from 1980 to 2013. IOTC-2014-WPTmT05-19.

Matsumoto, T., Nishida, T., Kitakado T. 2012. Stock and risk assessments of albacore in the Indian Ocean based on ASPIC. IOTC–2012–WPTmT04–20 Rev_1. 12pp.

Matsumoto, T., Kitakado, T. and Nishida, T. 2014. Standardization of albacore CPUE by Japanese longline fishery in the Indian Ocean. IOTC–2014–WPTmT05–18. 15pp.

McAllister, M. K., Pikitch, E. K. and Babcock, E. A. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58: 1871-1890.

Nishida, T. and Matsumoto, T. 2011. Stock and risk assessments of albacore tuna (*Thunnus alalunga*) in the Indian Ocean by A Stock-Production Model Incorporating Covariates (ASPIC). IOTC-2011-WPTmT03-17. 15pp.

Nishida, T., Rademeyer, R. 2012. Stock and risk assessments on albacore (*Thunnus alalunga*) in the Indian Ocean based on AD Model Builder implemented

Age-Structured Production Model (ASPM). IOTC–2012–WPTmT04–21 Rev_4. 15pp.
Nishida, T. Kitakado, T., Matsumoto, T. 2014. Consideration and proposal of biological parameters for the 2014 albacore stock assessment in the Indian Ocean. IOTC-2014-WPTmT05-xx. 15pp.
Prager M. 1994. A suite of extensions to a nonequilibrium surplus-production model. Fishery Bulletin (U.S.), 92: 374-389.

Appendix A:

A1: Summary for Scenario 1

	mean	sd	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
r	0.42089883	0.058191446	0.31800	0.37990	0.41780	0.45820	0.54300	1.001075	7600
q	0.08938950	0.015699812	0.05915	0.07923	0.08906	0.09921	0.12110	1.000860	8000
B0	0.92418159	0.067884347	0.74610	0.89210	0.94210	0.97600	0.99760	1.000984	8000
K	6.84451606	1.032545448	5.27200	6.18100	6.73300	7.35800	9.06700	1.000869	8000
Ft[1]	0.05075211	0.008075660	0.03636	0.04537	0.05015	0.05549	0.06863	1.000944	8000
Ft[2]	0.05537043	0.008358621	0.03968	0.04981	0.05493	0.06054	0.07326	1.000915	8000
Ft[3]	0.09450325	0.014067085	0.06772	0.08525	0.09398	0.10340	0.12360	1.000895	8000
Ft[4]	0.07847721	0.011637440	0.05606	0.07093	0.07812	0.08594	0.10200	1.000882	8000
Ft[5]	0.07003954	0.010236620	0.05017	0.06347	0.06981	0.07660	0.09046	1.000871	8000
Ft[6]	0.04436031	0.006325562	0.03202	0.04033	0.04427	0.04843	0.05692	1.000862	8000
Ft[7]	0.13280029	0.019150308	0.09543	0.12060	0.13250	0.14500	0.17090	1.000858	8000
Ft[8]	0.13203869	0.019700497	0.09376	0.11950	0.13170	0.14460	0.17130	1.000856	8000
Ft[9]	0.13103544	0.019890593	0.09240	0.11830	0.13070	0.14380	0.17080	1.000851	8000
Ft[10]	0.09514254	0.014343789	0.06698	0.08597	0.09496	0.10440	0.12370	1.000847	8000
Ft[11]	0.15838522	0.024033216	0.11100	0.14310	0.15800	0.17390	0.20610	1.000844	8000
Ft[12]	0.13735359	0.021178912	0.09538	0.12390	0.13700	0.15100	0.17930	1.000841	8000
Ft[13]	0.10444207	0.015903504	0.07253	0.09433	0.10430	0.11470	0.13560	1.000838	8000
Ft[14]	0.09222643	0.013666652	0.06452	0.08359	0.09216	0.10110	0.11870	1.000835	8000
Ft[15]	0.11669386	0.017048189	0.08189	0.10600	0.11670	0.12780	0.14950	1.000833	8000
Ft[16]	0.11018521	0.016034536	0.07720	0.10010	0.11020	0.12070	0.14100	1.000832	8000
Ft[17]	0.14465261	0.021228835	0.10100	0.13140	0.14470	0.15850	0.18550	1.000831	8000
Ft[18]	0.13615987	0.020252593	0.09442	0.12350	0.13620	0.14930	0.17520	1.000831	8000
Ft[19]	0.19267729	0.029533888	0.13190	0.17410	0.19280	0.21200	0.24970	1.000831	8000
Ft[20]	0.20341348	0.032657143	0.13620	0.18280	0.20350	0.22470	0.26690	1.000831	8000
Ft[21]	0.21376034	0.035847956	0.14020	0.19090	0.21380	0.23710	0.28390	1.000830	8000
Ft[22]	0.26255894	0.046868188	0.16830	0.23230	0.26230	0.29290	0.35580	1.000830	8000
Ft[23]	0.22342141	0.042194691	0.13900	0.19600	0.22290	0.25070	0.30710	1.000830	8000
Ft[24]	0.17412985	0.033266674	0.10700	0.15240	0.17390	0.19580	0.23990	1.000828	8000
Ft[25]	0.17813854	0.033786247	0.11020	0.15620	0.17810	0.20010	0.24540	1.000826	8000
Ft[26]	0.17205907	0.032422185	0.10640	0.15100	0.17220	0.19330	0.23640	1.000824	8000
Ft[27]	0.17325197	0.032425071	0.10740	0.15220	0.17350	0.19460	0.23700	1.000822	8000
Ft[28]	0.22764076	0.043526458	0.13960	0.19920	0.22770	0.25630	0.31350	1.000821	8000
Ft[29]	0.21925728	0.043672432	0.13200	0.19050	0.21910	0.24810	0.30660	1.000821	8000
Ft[30]	0.24101464	0.050386131	0.14200	0.20740	0.24050	0.27410	0.34370	1.000820	8000
Ft[31]	0.29654714	0.067838320	0.16780	0.25060	0.29430	0.34000	0.43900	1.000820	8000
Ft[32]	0.23960460	0.060362339	0.13020	0.19860	0.23550	0.27640	0.37070	1.000820	8000
Ft[33]	0.24729318	0.068105950	0.13050	0.20120	0.24030	0.28600	0.40230	1.000820	8000
B[1]	6.33005437	1.091679139	4.46100	5.63200	6.25500	6.92400	8.62700	1.000962	8000
B[2]	6.22754431	1.042448681	4.56600	5.54900	6.13600	6.76900	8.47200	1.000928	8000
B[3]	6.13791464	1.011929926	4.56800	5.48300	6.03400	6.64400	8.34700	1.000904	8000
B[4]	5.88710036	0.990259611	4.40900	5.24900	5.77800	6.37100	8.04000	1.000888	8000
B[5]	5.79451456	0.973634275	4.36800	5.16700	5.68200	6.25500	7.92200	1.000876	8000
B[6]	5.77018723	0.961345429	4.37700	5.15900	5.65500	6.21400	7.85000	1.000866	8000
B[7]	5.87568966	0.953695834	4.49800	5.27300	5.75900	6.31300	7.93500	1.000859	8000
B[8]	5.53256605	0.945733664	4.17500	4.93800	5.41500	5.96100	7.56800	1.000857	8000
B[9]	5.30419448	0.936180482	3.97600	4.71600	5.18500	5.72600	7.30600	1.000853	8000
B[10]	5.14921947	0.927230792	3.84400	4.56900	5.03100	5.56000	7.14400	1.000850	8000
B[11]	5.19205699	0.919961992	3.91000	4.62000	5.07200	5.59600	7.18000	1.000845	8000
B[12]	4.95382327	0.913419861	3.69400	4.38800	4.83600	5.35100	6.92600	1.000843	8000
B[13]	4.87038058	0.907836896	3.63400	4.31100	4.75200	5.25800	6.84200	1.000840	8000
B[14]	4.94384177	0.903207659	3.72600	4.39100	4.82400	5.32600	6.91700	1.000837	8000
B[15]	5.04973516	0.899567838	3.84500	4.49900	4.93000	5.42900	7.02100	1.000834	8000
B[16]	5.02434008	0.896559577	3.82700	4.47600	4.90400	5.39900	6.99700	1.000833	8000
B[17]	5.03293338	0.894114311	3.84300	4.48700	4.91100	5.40400	7.01400	1.000831	8000
B[18]	4.89524997	0.891684346	3.71400	4.35200	4.77200	5.26200	6.86600	1.000831	8000
B[19]	4.83018248	0.889591386	3.65700	4.29100	4.70400	5.19200	6.80100	1.000830	8000
B[20]	4.55936408	0.888067821	3.40100	4.02200	4.43000	4.91700	6.54400	1.000831	8000
B[21]	4.32580640	0.888485343	3.17600	3.79000	4.19200	4.67900	6.31700	1.000830	8000
B[22]	4.11887852	0.891490326	2.97700	3.58200	3.98000	4.47200	6.12300	1.000830	8000
B[23]	3.80387477	0.899342991	2.66900	3.26300	3.66300	4.15400	5.81000	1.000831	8000
B[24]	3.69529434	0.911760175	2.56200	3.14800	3.54600	4.04700	5.75000	1.000830	8000
B[25]	3.76657518	0.923596969	2.61800	3.21200	3.61000	4.11900	5.84100	1.000827	8000
B[26]	3.81030996	0.932683815	2.65300	3.25100	3.65100	4.16300	5.90800	1.000825	8000
B[27]	3.86454718	0.939494378	2.70100	3.29900	3.70100	4.22300	5.97800	1.000823	8000
B[28]	3.90322447	0.944425835	2.74200	3.33400	3.74100	4.26000	6.03600	1.000821	8000
B[29]	3.75551556	0.951256812	2.58100	3.18000	3.59100	4.11700	5.91300	1.000821	8000
B[30]	3.66908686	0.962100903	2.48300	3.08400	3.49900	4.03900	5.85000	1.000820	8000

B[31]	3.53610311	0.977266289	2.32600	2.93700	3.36200	3.91400	5.75800	1.000820	8000
B[32]	3.27695601	1.001995694	2.01600	2.66100	3.10700	3.67200	5.56200	1.000820	8000
B[33]	3.23571304	1.034897656	1.89900	2.59900	3.06500	3.65000	5.59700	1.000820	8000
B[34]	3.18422463	1.071962366	1.74300	2.52400	3.02300	3.62700	5.62800	1.000820	8000
Tau	10.49309899	2.792486375	5.79200	8.47800	10.26000	12.23000	16.58000	1.000879	8000
deviance	-43.96989001	3.478216528	-48.52000	-46.49000	-44.69000	-42.26000	-35.18000	1.001237	4800

A2: Gelman and Rubin's convergence diagnostic for Scenario 1

Potential scale reduction factors:

	Point est.	Upper C.I.
r	1.00	1.00
q	1.00	1.00
B0	1.00	1.00
K	1.00	1.00
Ft[1]	1.00	1.00
Ft[2]	1.00	1.00
Ft[3]	1.00	1.00
Ft[4]	1.00	1.00
Ft[5]	1.00	1.00
Ft[6]	1.00	1.00
Ft[7]	1.00	1.00
Ft[8]	1.00	1.00
Ft[9]	1.00	1.00
Ft[10]	1.00	1.00
Ft[11]	1.00	1.00
Ft[12]	1.00	1.00
Ft[13]	1.00	1.00
Ft[14]	1.00	1.00
Ft[15]	1.00	1.00
Ft[16]	1.00	1.00
Ft[17]	1.00	1.00
Ft[18]	1.00	1.00
Ft[19]	1.00	1.00
Ft[20]	1.00	1.00
Ft[21]	1.00	1.00
Ft[22]	1.00	1.00
Ft[23]	1.00	1.00
Ft[24]	1.00	1.00
Ft[25]	1.00	1.00
Ft[26]	1.00	1.00
Ft[27]	1.00	1.00
Ft[28]	1.00	1.00
Ft[29]	1.00	1.00
Ft[30]	1.00	1.00
Ft[31]	1.00	1.00
Ft[32]	1.00	1.00
Ft[33]	1.00	1.00
B[1]	1.00	1.00
B[2]	1.00	1.00
B[3]	1.00	1.00
B[4]	1.00	1.00
B[5]	1.00	1.00
B[6]	1.00	1.00
B[7]	1.00	1.00
B[8]	1.00	1.01
B[9]	1.00	1.01
B[10]	1.00	1.01
B[11]	1.00	1.01
B[12]	1.01	1.01
B[13]	1.01	1.01
B[14]	1.01	1.01
B[15]	1.01	1.01
B[16]	1.01	1.01
B[17]	1.01	1.01
B[18]	1.01	1.01
B[19]	1.01	1.01
B[20]	1.01	1.01
B[21]	1.01	1.01
B[22]	1.01	1.01
B[23]	1.01	1.01
B[24]	1.01	1.01
B[25]	1.01	1.01

B[26]	1.01	1.01
B[27]	1.01	1.01
B[28]	1.00	1.01
B[29]	1.00	1.01
B[30]	1.00	1.00
B[31]	1.00	1.00
B[32]	1.00	1.00
B[33]	1.00	1.00
B[34]	1.00	1.00
Tau	1.00	1.00
deviance	1.00	1.00

Multivariate psrf

1.02

A3: Summary for Scenario 5

> RBM1$summary

	mean	sd	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
r	0.41193193	0.050819887	0.31820999	0.3758000	0.410200	0.4475000	0.5125975	1.000907	7000
q	0.12868671	0.022601611	0.08431050	0.1137000	0.128700	0.1442000	0.1724000	1.000837	7000
B0	0.91714981	0.074812563	0.72290000	0.8820000	0.938600	0.9736000	0.9977000	1.002324	4600
K	5.18873793	0.726535407	4.13000000	4.6692500	5.090000	5.5850000	6.8479250	1.000794	7000
Ft[1]	0.06778615	0.010861899	0.04899100	0.0605525	0.067220	0.0744000	0.0903695	1.000907	7000
Ft[2]	0.07458957	0.011099724	0.05396075	0.0671000	0.074310	0.0819375	0.0962695	1.000871	7000
Ft[3]	0.12894939	0.018854552	0.09278025	0.1161000	0.128900	0.1419000	0.1645000	1.000849	7000
Ft[4]	0.10831588	0.015775934	0.07750150	0.0976225	0.108300	0.1193000	0.1377000	1.000837	7000
Ft[5]	0.09704282	0.013887930	0.06952000	0.0875825	0.097180	0.1069000	0.1226000	1.000831	7000
Ft[6]	0.06128568	0.008503513	0.04421075	0.0555900	0.061425	0.0673800	0.0768500	1.000827	7000
Ft[7]	0.18523983	0.026183325	0.13220250	0.1676000	0.185600	0.2041000	0.2332000	1.000823	7000
Ft[8]	0.18776334	0.027821924	0.13160250	0.1691000	0.188000	0.2078000	0.2389975	1.000823	7000
Ft[9]	0.18858351	0.028632724	0.13080250	0.1695000	0.188900	0.2093000	0.2410975	1.000826	7000
Ft[10]	0.13688612	0.020582096	0.09507100	0.1232250	0.137200	0.1517000	0.1742975	1.000829	7000
Ft[11]	0.22928786	0.034879900	0.15770250	0.2061000	0.229900	0.2544000	0.2923000	1.000833	7000
Ft[12]	0.20066423	0.031231398	0.13640000	0.1800000	0.201400	0.2230000	0.2571000	1.000837	7000
Ft[13]	0.15173800	0.023207470	0.10340250	0.1366000	0.152400	0.1684000	0.1933000	1.000842	7000
Ft[14]	0.13241676	0.019529940	0.09116475	0.1199000	0.133200	0.1465000	0.1671000	1.000846	7000
Ft[15]	0.16677083	0.024209746	0.11540500	0.1513000	0.167800	0.1842750	0.2095000	1.000847	7000
Ft[16]	0.15738195	0.022778047	0.10920000	0.1428000	0.158400	0.1738000	0.1975000	1.000849	7000
Ft[17]	0.20768966	0.030500110	0.14350500	0.1881250	0.209000	0.2296750	0.2616000	1.000849	7000
Ft[18]	0.19677815	0.029476373	0.13530250	0.1778250	0.198100	0.2179000	0.2492000	1.000852	7000
Ft[19]	0.28235933	0.044148069	0.19080250	0.2538000	0.284200	0.3139000	0.3618975	1.000854	7000
Ft[20]	0.30413695	0.050698783	0.20050749	0.2711000	0.305900	0.3401750	0.3967975	1.000859	7000
Ft[21]	0.32471248	0.057410594	0.20870000	0.2870000	0.326200	0.3655750	0.4309975	1.000866	7000
Ft[22]	0.40791314	0.078614773	0.25160250	0.3554000	0.408750	0.4628000	0.5566000	1.000874	7000
Ft[23]	0.35097923	0.072648391	0.20860000	0.3021250	0.350800	0.4006000	0.4920975	1.000883	7000
Ft[24]	0.26819794	0.055539844	0.15950250	0.2312000	0.268200	0.3064000	0.3758000	1.000895	7000
Ft[25]	0.26709059	0.053785342	0.16090000	0.2315000	0.267500	0.3040000	0.3706975	1.000906	7000
Ft[26]	0.25243235	0.049493025	0.15380500	0.2197250	0.253200	0.2864000	0.3470975	1.000915	7000
Ft[27]	0.24975629	0.047697317	0.15391497	0.2185000	0.250650	0.2824750	0.3404950	1.000922	7000
Ft[28]	0.32728836	0.063378618	0.20051498	0.2857000	0.328300	0.3707750	0.4480775	1.000926	7000
Ft[29]	0.31552434	0.063295548	0.19080000	0.2738000	0.316000	0.3589000	0.4371925	1.000930	7000
Ft[30]	0.34617099	0.072225059	0.20570250	0.2982000	0.345700	0.3949000	0.4872925	1.000935	7000
Ft[31]	0.42855634	0.097572787	0.24520250	0.3625000	0.425400	0.4929750	0.6277925	1.000940	7000
Ft[32]	0.34249144	0.083756963	0.19021248	0.2855000	0.338150	0.3957000	0.5185925	1.000948	7000
Ft[33]	0.34336945	0.087007592	0.18970000	0.2847000	0.337100	0.3959750	0.5306925	1.000959	7000
B[1]	4.76379420	0.800993492	3.37812491	4.2242500	4.698000	5.2210000	6.4310000	1.000930	7000
B[2]	4.63962339	0.748020075	3.46107497	4.1250000	4.552000	5.0497500	6.2599250	1.000887	7000
B[3]	4.53504841	0.715870493	3.46509994	4.0350000	4.441500	4.9220000	6.1338499	1.000858	7000
B[4]	4.27682062	0.693339922	3.27304999	3.7910000	4.180500	4.6397500	5.8349250	1.000842	7000
B[5]	4.18216324	0.676269022	3.22202500	3.7090000	4.083500	4.5320000	5.7119750	1.000834	7000
B[6]	4.15749143	0.664032646	3.22702500	3.6920000	4.060000	4.4990000	5.6609750	1.000829	7000
B[7]	4.26124750	0.656662376	3.34502500	3.8030000	4.163000	4.5957500	5.7718499	1.000825	7000
B[8]	3.92141045	0.648863008	3.02302500	3.4680000	3.823000	4.2460000	5.4210000	1.000822	7000
B[9]	3.70415738	0.639383132	2.82904998	3.2590000	3.606500	4.0167500	5.1859000	1.000824	7000
B[10]	3.56436033	0.630683583	2.71200000	3.1270000	3.467000	3.8660000	5.0249000	1.000827	7000
B[11]	3.62050628	0.623932408	2.78702500	3.1910000	3.523000	3.9150000	5.0769250	1.000831	7000
B[12]	3.39760440	0.618006362	2.58000000	2.9750000	3.297000	3.6877500	4.8499750	1.000834	7000
B[13]	3.33270965	0.612941817	2.53000000	2.9160000	3.229000	3.6120000	4.7848749	1.000839	7000
B[14]	3.42071123	0.609149552	2.62802500	3.0072500	3.316000	3.6930000	4.8717998	1.000844	7000
B[15]	3.53384247	0.606600755	2.74602500	3.1230000	3.429000	3.8030000	4.9837498	1.000847	7000
B[16]	3.51269252	0.604769791	2.73000000	3.1040000	3.407500	3.7810000	4.9519750	1.000848	7000
B[17]	3.52497729	0.603313647	2.74500000	3.1180000	3.420000	3.7920000	4.9499750	1.000849	7000

B[18]	3.39386518	0.601714295	2.61702500	2.9890000	3.288000	3.6580000	4.8069750	1.000850	7000
B[19]	3.33878692	0.600135331	2.56600000	2.9360000	3.230000	3.6010000	4.7399750	1.000853	7000
B[20]	3.08536547	0.598672266	2.31702499	2.6852500	2.975500	3.3447500	4.4829000	1.000856	7000
B[21]	2.87911411	0.598615024	2.11702499	2.4810000	2.768000	3.1337500	4.2679750	1.000862	7000
B[22]	2.70687175	0.600831204	1.94704997	2.3090000	2.593000	2.9587500	4.1039000	1.000870	7000
B[23]	2.43616281	0.607357284	1.67000000	2.0370000	2.321000	2.6877500	3.8699500	1.000878	7000
B[24]	2.37763882	0.617811880	1.60000000	1.9730000	2.261000	2.6320000	3.8357497	1.000888	7000
B[25]	2.49523336	0.626245974	1.70302499	2.0850000	2.376000	2.7507500	3.9738749	1.000901	7000
B[26]	2.57759254	0.630653583	1.78002499	2.1662500	2.457000	2.8350000	4.0699250	1.000911	7000
B[27]	2.66319509	0.632142934	1.86200000	2.2520000	2.541000	2.9200000	4.1596494	1.000919	7000
B[28]	2.72645516	0.631492476	1.92702499	2.3150000	2.605000	2.9830000	4.2216996	1.000924	7000
B[29]	2.60580620	0.632021666	1.80800000	2.1932500	2.484000	2.8620000	4.1037246	1.000927	7000
B[30]	2.55308398	0.635105855	1.74902499	2.1372500	2.432000	2.8110000	4.0489750	1.000933	7000
B[31]	2.46017666	0.640491969	1.64102499	2.0412500	2.341000	2.7220000	3.9669250	1.000938	7000
B[32]	2.25505727	0.651845856	1.41000000	1.8300000	2.137500	2.5277500	3.7888749	1.000943	7000
B[33]	2.27716414	0.666661593	1.39600000	1.8440000	2.161500	2.5590000	3.8428499	1.000953	7000
B[34]	2.29120486	0.680004666	1.36702499	1.8540000	2.179500	2.5820000	3.8729750	1.000964	7000
Tau	11.19574336	2.941159110	6.11902500	9.1040000	10.900000	13.0300000	17.4797499	1.000959	7000
deviance	-46.23564125	3.359010684	-50.76000000	-48.6600000	-46.895000	-44.5500000	-37.8600000	1.000943	7000

A4: Gelman and Rubin's convergence diagnostic for Scenario 5

Potential scale reduction factors:

	Point est.	Upper C.I.
r	1	1.00
q	1	1.00
B0	1	1.01
K	1	1.00
Ft[1]	1	1.00
Ft[2]	1	1.00
Ft[3]	1	1.00
Ft[4]	1	1.00
Ft[5]	1	1.00
Ft[6]	1	1.00
Ft[7]	1	1.00
Ft[8]	1	1.00
Ft[9]	1	1.00
Ft[10]	1	1.00
Ft[11]	1	1.00
Ft[12]	1	1.00
Ft[13]	1	1.00
Ft[14]	1	1.00
Ft[15]	1	1.00
Ft[16]	1	1.00
Ft[17]	1	1.00
Ft[18]	1	1.00
Ft[19]	1	1.00
Ft[20]	1	1.00
Ft[21]	1	1.00
Ft[22]	1	1.00
Ft[23]	1	1.00
Ft[24]	1	1.00
Ft[25]	1	1.00
Ft[26]	1	1.00
Ft[27]	1	1.00
Ft[28]	1	1.00
Ft[29]	1	1.00
Ft[30]	1	1.00
Ft[31]	1	1.00
Ft[32]	1	1.00
Ft[33]	1	1.00
B[1]	1	1.00
B[2]	1	1.00
B[3]	1	1.00
B[4]	1	1.00
B[5]	1	1.00
B[6]	1	1.00
B[7]	1	1.00
B[8]	1	1.00
B[9]	1	1.00
B[10]	1	1.00
B[11]	1	1.00
B[12]	1	1.00

B[13]	1	1.00
B[14]	1	1.01
B[15]	1	1.01
B[16]	1	1.01
B[17]	1	1.01
B[18]	1	1.01
B[19]	1	1.01
B[20]	1	1.01
B[21]	1	1.01
B[22]	1	1.01
B[23]	1	1.01
B[24]	1	1.01
B[25]	1	1.01
B[26]	1	1.01
B[27]	1	1.01
B[28]	1	1.01
B[29]	1	1.01
B[30]	1	1.01
B[31]	1	1.01
B[32]	1	1.01
B[33]	1	1.01
B[34]	1	1.01
Tau	1	1.00
deviance	1	1.00

Multivariate psrf

1.02

A5: **Summary for Scenario 10**

> RBM3$summary

	mean	sd	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
r	0.41646207	0.056999959	0.31710500	0.3761250	0.412000	0.4525750	0.54050000	1.000966	7000
q	0.13091147	0.024357567	0.08512250	0.1147000	0.130000	0.1463000	0.18229750	1.000895	7000
B0	0.91692916	0.076750612	0.71700250	0.8812250	0.938400	0.9749750	0.99780000	1.000793	7000
K	5.13256213	0.738967890	3.89502500	4.6230000	5.066000	5.5597500	6.74300000	1.000887	7000
Ft[1]	0.06874257	0.011801077	0.04917075	0.0607300	0.067555	0.0754100	0.09529975	1.000853	7000
Ft[2]	0.07565022	0.012147775	0.05443000	0.0673100	0.074800	0.0830175	0.10220000	1.000863	7000
Ft[3]	0.13083648	0.020754051	0.09381125	0.1166000	0.129500	0.1439000	0.17579750	1.000870	7000
Ft[4]	0.10992842	0.017406313	0.07864275	0.0982025	0.108950	0.1209000	0.14729750	1.000873	7000
Ft[5]	0.09846798	0.015309240	0.07049100	0.0881000	0.097765	0.1083000	0.13040000	1.000876	7000
Ft[6]	0.06215423	0.009350076	0.04487025	0.0558900	0.061795	0.0681175	0.08145925	1.000875	7000
Ft[7]	0.18794541	0.028861003	0.13480250	0.1686000	0.187000	0.2061000	0.24790000	1.000877	7000
Ft[8]	0.19067254	0.030751592	0.13430000	0.1702000	0.189400	0.2100000	0.25500000	1.000878	7000
Ft[9]	0.19157643	0.031620985	0.13310500	0.1704000	0.190200	0.2116000	0.25789500	1.000878	7000
Ft[10]	0.13900660	0.022621667	0.09661050	0.1238000	0.138200	0.1535000	0.18600000	1.000877	7000
Ft[11]	0.23287328	0.038287735	0.16080250	0.2071000	0.231500	0.2573000	0.31219750	1.000876	7000
Ft[12]	0.20386701	0.034240740	0.13950250	0.1808000	0.202800	0.2257000	0.27480000	1.000876	7000
Ft[13]	0.15407729	0.025309254	0.10600000	0.1372000	0.153400	0.1703000	0.20599500	1.000875	7000
Ft[14]	0.13435160	0.021187284	0.09342025	0.1203000	0.134000	0.1480000	0.17720000	1.000874	7000
Ft[15]	0.16916102	0.026226601	0.11810250	0.1518250	0.168800	0.1861000	0.22200000	1.000874	7000
Ft[16]	0.15963338	0.024670581	0.11150000	0.1434000	0.159300	0.1756000	0.20930000	1.000875	7000
Ft[17]	0.21072267	0.033081254	0.14630250	0.1890000	0.210200	0.2321000	0.27759750	1.000876	7000
Ft[18]	0.19971679	0.031987836	0.13750250	0.1787000	0.199100	0.2205000	0.26440000	1.000877	7000
Ft[19]	0.28679749	0.048017774	0.19420999	0.2550250	0.285800	0.3178000	0.38459750	1.000879	7000
Ft[20]	0.30927572	0.055276516	0.20350749	0.2724000	0.307900	0.3447000	0.42330000	1.000881	7000
Ft[21]	0.33053320	0.062628951	0.21120749	0.2886500	0.328700	0.3705000	0.46129000	1.000885	7000
Ft[22]	0.41594933	0.086060263	0.25620000	0.3586000	0.412350	0.4698000	0.59789000	1.000892	7000
Ft[23]	0.35835825	0.079552571	0.21290250	0.3047000	0.354450	0.4073000	0.52859750	1.000900	7000
Ft[24]	0.27361591	0.060265756	0.16300500	0.2331250	0.270800	0.3107750	0.40259750	1.000907	7000
Ft[25]	0.27209978	0.057737662	0.16470999	0.2336000	0.270000	0.3081750	0.39439500	1.000913	7000
Ft[26]	0.25687156	0.052682357	0.15780000	0.2218000	0.255400	0.2903000	0.36699250	1.000920	7000
Ft[27]	0.25391707	0.050448155	0.15790250	0.2203250	0.252900	0.2862000	0.35789500	1.000925	7000
Ft[28]	0.33276247	0.066927301	0.20580000	0.2881250	0.331400	0.3754000	0.47149500	1.000932	7000
Ft[29]	0.32093078	0.066773573	0.19550000	0.2763000	0.319250	0.3631000	0.46089250	1.000943	7000
Ft[30]	0.35224205	0.076087997	0.21110000	0.3011250	0.349700	0.4003750	0.51429250	1.000955	7000
Ft[31]	0.43665303	0.102964055	0.25200500	0.3668000	0.430800	0.4995000	0.66269250	1.000978	7000
Ft[32]	0.34918413	0.088194806	0.19590250	0.2894250	0.342600	0.4010000	0.54699750	1.001005	7000
Ft[33]	0.34995060	0.091102922	0.19500250	0.2885250	0.341950	0.4023000	0.55828249	1.001033	7000
B[1]	4.71121794	0.813534363	3.22309994	4.1660000	4.668000	5.2037500	6.40487495	1.000846	7000
B[2]	4.58694873	0.758656603	3.27100000	4.0740000	4.530000	5.0310000	6.22400000	1.000858	7000
B[3]	4.48272037	0.724444413	3.26102500	3.9832500	4.420000	4.9040000	6.05200000	1.000867	7000

B[4]	4.22528035	0.699475184	3.06102500	3.7390000	4.158000	4.6187500	5.76397500	1.000873	7000
B[5]	4.13156198	0.679919564	3.02402500	3.6610000	4.059500	4.5050000	5.62794999	1.000875	7000
B[6]	4.10764596	0.665673094	3.03702500	3.6500000	4.035000	4.4720000	5.58800000	1.000876	7000
B[7]	4.21177692	0.657154360	3.15604998	3.7630000	4.137000	4.5690000	5.67389997	1.000876	7000
B[8]	3.87259040	0.647779110	2.83602500	3.4322500	3.796000	4.2197500	5.32164955	1.000878	7000
B[9]	3.65631791	0.635987908	2.64702500	3.2230000	3.582500	3.9927500	5.08594999	1.000878	7000
B[10]	3.51750171	0.624864651	2.53604998	3.0920000	3.441500	3.8460000	4.94194999	1.000877	7000
B[11]	3.57437075	0.616262222	2.61502500	3.1560000	3.497000	3.8987500	4.99184991	1.000876	7000
B[12]	3.35217552	0.608510613	2.41200000	2.9400000	3.274000	3.6690000	4.74887494	1.000877	7000
B[13]	3.28795401	0.601538479	2.36802499	2.8810000	3.208000	3.5977500	4.66900000	1.000876	7000
B[14]	3.37641888	0.596375703	2.47200000	2.9760000	3.296000	3.6790000	4.75194999	1.000875	7000
B[15]	3.48974122	0.593272499	2.59202500	3.0910000	3.410000	3.7890000	4.86592498	1.000874	7000
B[16]	3.46866324	0.591195123	2.57502500	3.0720000	3.388000	3.7650000	4.84392498	1.000875	7000
B[17]	3.48101671	0.589551203	2.59100000	3.0852500	3.401000	3.7750000	4.85397500	1.000875	7000
B[18]	3.35006327	0.587466702	2.46502500	2.9550000	3.269000	3.6417500	4.72194999	1.000876	7000
B[19]	3.29523993	0.585115457	2.41702499	2.9020000	3.214000	3.5830000	4.66484991	1.000877	7000
B[20]	3.04224036	0.582354590	2.17700000	2.6510000	2.958000	3.3287500	4.40300000	1.000880	7000
B[21]	2.83645444	0.580506576	1.98002499	2.4480000	2.748500	3.1190000	4.21097500	1.000883	7000
B[22]	2.66459869	0.580779482	1.81902499	2.2762500	2.575000	2.9377500	4.04192497	1.000887	7000
B[23]	2.39404927	0.585314408	1.55402499	2.0040000	2.298000	2.6660000	3.78979979	1.000896	7000
B[24]	2.33543426	0.594004747	1.48702499	1.9430000	2.237000	2.6080000	3.75397500	1.000905	7000
B[25]	2.45307969	0.601006887	1.59800000	2.0570000	2.353000	2.7247500	3.87700000	1.000910	7000
B[26]	2.53566538	0.604319095	1.68000000	2.1360000	2.434000	2.8087500	3.96884989	1.000917	7000
B[27]	2.62156298	0.605017461	1.76502499	2.2202500	2.519000	2.8960000	4.05494999	1.000922	7000
B[28]	2.68512154	0.603854944	1.83502499	2.2870000	2.582000	2.9590000	4.11694999	1.000927	7000
B[29]	2.56474836	0.603817617	1.71404997	2.1680000	2.461000	2.8370000	3.99697500	1.000937	7000
B[30]	2.51223536	0.606223105	1.65804997	2.1120000	2.406000	2.7840000	3.95192497	1.000948	7000
B[31]	2.41946073	0.610873231	1.55800000	2.0142500	2.313500	2.6960000	3.86494999	1.000962	7000
B[32]	2.21428123	0.621384891	1.33402499	1.8032499	2.108500	2.4970000	3.67797500	1.000991	7000
B[33]	2.23620384	0.635443710	1.32300000	1.8170000	2.130000	2.5230000	3.72900000	1.001017	7000
B[34]	2.25017284	0.648228260	1.30000000	1.8230000	2.148000	2.5460000	3.77097500	1.001047	7000
Tau	11.14941117	2.919253493	6.05900000	9.0332500	10.920000	12.9700000	17.47000000	1.001006	7000
deviance	-46.21958726	3.367332335	-50.78000000	-48.6900000	-46.890000	-44.4625000	-38.06050000	1.001007	7000

A6: Gelman and Rubin's convergence diagnostic for Scenario 10

Potential scale reduction factors:

	Point est.	Upper C.I.
r	1	1
q	1	1
B0	1	1
K	1	1
Ft[1]	1	1
Ft[2]	1	1
Ft[3]	1	1
Ft[4]	1	1
Ft[5]	1	1
Ft[6]	1	1
Ft[7]	1	1
Ft[8]	1	1
Ft[9]	1	1
Ft[10]	1	1
Ft[11]	1	1
Ft[12]	1	1
Ft[13]	1	1
Ft[14]	1	1
Ft[15]	1	1
Ft[16]	1	1
Ft[17]	1	1
Ft[18]	1	1
Ft[19]	1	1
Ft[20]	1	1
Ft[21]	1	1
Ft[22]	1	1
Ft[23]	1	1
Ft[24]	1	1
Ft[25]	1	1
Ft[26]	1	1
Ft[27]	1	1
Ft[28]	1	1
Ft[29]	1	1
Ft[30]	1	1
Ft[31]	1	1

Ft[32]	1	1
Ft[33]	1	1
B[1]	1	1
B[2]	1	1
B[3]	1	1
B[4]	1	1
B[5]	1	1
B[6]	1	1
B[7]	1	1
B[8]	1	1
B[9]	1	1
B[10]	1	1
B[11]	1	1
B[12]	1	1
B[13]	1	1
B[14]	1	1
B[15]	1	1
B[16]	1	1
B[17]	1	1
B[18]	1	1
B[19]	1	1
B[20]	1	1
B[21]	1	1
B[22]	1	1
B[23]	1	1
B[24]	1	1
B[25]	1	1
B[26]	1	1
B[27]	1	1
B[28]	1	1
B[29]	1	1
B[30]	1	1
B[31]	1	1
B[32]	1	1
B[33]	1	1
B[34]	1	1
Tau	1	1
deviance	1	1

Multivariate psrf

1.02

Appendix B:
The winBUGS code for Continuous Logistic-form and Fox-form biomass dynamics models:

B1: the script for PragerPMFB Function

```
(*1*)   MODULE WBDevPragerPMFB;

            IMPORT
                WBDevVector,
(*2*)           Math;

            TYPE
                Function = POINTER TO RECORD (WBDevVector.Node) END;
                Factory = POINTER TO RECORD (WBDevVector.Factory) END;

            VAR
                fact-: WBDevVector.Factory;

(*3*)       PROCEDURE (func: Function) DeclareArgTypes (OUT args: ARRAY OF CHAR);
(*4*)       BEGIN
(*5*)           args := "ssss";
(*6*)       END DeclareArgTypes;

(*7*)       PROCEDURE (func: Function) Evaluate (OUT values: ARRAY OF REAL);
(*8*)       CONST
(*9*)           (*parameters = 0; dose = 1; times = 2;*)
                    MINVALUE=0.000000001;
(*10*)      VAR
(*11*)          r, K, Yt, Bt, Fest,beta, alpha, RT, lnRR, lnR,F,BN: REAL;
                    Count: INTEGER;
(*13*)      BEGIN
(*14*)          r       := func.arguments[0][0].Value();
                    K    := func.arguments[1][0].Value();
                    Yt := func.arguments[2][0].Value();
                    Bt := func.arguments[3][0].Value();

                    IF     ( Bt < Yt)    THEN;
                        F:=5.0;
                        BN:=0.0001;
                    ELSE;
                        beta := r/K;
                        F:= r;
                        RT      := 10;
                        Count :=0;
                        WHILE (RT>0.001 )    & (Count<50) DO
                                Fest:= F;
                                alpha:=r-Fest;
                                IF ABS(alpha)<    0.0001 THEN;
                                    F:=beta*Yt/Math.Ln(1+beta*Bt);
                                ELSE;
                                    lnRR :=beta*Bt*(Math.Exp(alpha)-1)/alpha+1;
                                    lnR      :=Math.Ln(lnRR);
                                    F           :=beta*Yt/lnR;
                                END;
                                Count:=Count+1;
                                RT:= ABS( F-Fest);
                         END;
                         alpha:=r-F;
                         IF ABS(alpha)<    0.0001 THEN;
                                BN := Bt/(1+beta*Bt);
                         ELSE;
                                BN:=alpha*Bt*Math.Exp(alpha)/(alpha+beta*Bt*(Math.Exp(alpha)-1.0));
                         END;
                   END;
(*31*)          values[0] :=BN ;
(*32*)          values[1] :=F ;
(*33*)      END Evaluate;

            PROCEDURE (f: Factory) New (option: INTEGER): Function;
            VAR
```

```
                func: Function;
            BEGIN
                NEW(func); func.Initialize; RETURN func;
            END New;

            PROCEDURE Install*;
            BEGIN
                WBDevVector.Install(fact);
            END Install;

            PROCEDURE Init;
            VAR
                f: Factory;
            BEGIN
                NEW(f); fact := f;
            END Init;

        BEGIN
            Init;
(*1*)   END WBDevPragerPMFB.
```

B2: the script for FoxPMFB Function

```
(*1*)   MODULE WBDevFoxPMFB;

            IMPORT
                WBDevVector,
(*2*)           Math;

            TYPE
                Function = POINTER TO RECORD (WBDevVector.Node) END;
                Factory = POINTER TO RECORD (WBDevVector.Factory) END;

            VAR
                fact-: WBDevVector.Factory;

(*3*)       PROCEDURE (func: Function) DeclareArgTypes (OUT args: ARRAY OF CHAR);
(*4*)       BEGIN
(*5*)           args := "ssss";
(*6*)       END DeclareArgTypes;

(*7*)       PROCEDURE (func: Function) Evaluate (OUT values: ARRAY OF REAL);
(*8*)       CONST
(*9*)           (*parameters = 0; dose = 1; times = 2;*)

(*10*)      VAR
(*11*)          i,N,N2: INTEGER;
(*12*)          r,K,Yt,Bt, A, F, Fest, D, RT, lnK, lnB, Delta,InSF,InSO,InSE,InR: REAL;
                   rT, B: ARRAY 51 OF REAL;
(*13*)      BEGIN
(*14*)          r      := func.arguments[0][0].Value();
                    K    := func.arguments[1][0].Value();
                    Yt := func.arguments[2][0].Value();
                    Bt := func.arguments[3][0].Value();
                    (*NR    := func.arguments[4][0].Value()+0.00001;*)
                    RT :=10;
                    N := 50; (*TRUNC(NR);*)
(*15*)          N2 := N DIV 2;
                    (*N1 :=N+1;*)
(*16*)           lnK :=Math.Ln(K);
(*17*)           lnB :=Math.Ln(Bt);
(*18*)          Delta :=(1.0-0.0)/N;
(*19*)          FOR   i :=0    TO N DO
                          rT[i] := (-r)*Delta*i;
                    END;
                    F:= r;
(*20*)          WHILE RT > 0.00001 DO;
(*21*)              Fest :=F;
(*22*)              A :=lnK*r-Fest;
(*23*)                D :=A- r*lnB;
                        FOR i :=0 TO N DO
                              B[i] :=Math.Exp((A-Math.Exp(rT[i])*D)/r);
                        END;
```

```
(*24*)                      InSF :=B[0] +B[N];
                                  InSO :=0;
(*25*)                      FOR i :=1 TO N2    DO
(*26*)                              InSO :=InSO+B[(i-1)*2+1];
                                  END;
                                  InSE :=0;
(*27*)                    FOR i:=1 TO N2-1 DO
(*28*)                          InSE := InSE+B[i*2];
(*29*)                    END;
                                 InR := Delta/3.0*(InSF+InSO*4+InSE*2);
                                 F :=Yt/MAX(InR,0.000001);
                                 RT :=ABS(F-Fest);
(*30*)               END;
(*31*)               values[0] :=B[N] ;
(*32*)               values[1] :=Fest ;
(*33*)          END Evaluate;

                PROCEDURE (f: Factory) New (option: INTEGER): Function;
                VAR
                     func: Function;
                BEGIN
                     NEW(func); func.Initialize; RETURN func;
                END New;

                PROCEDURE Install*;
                BEGIN
                     WBDevVector.Install(fact);
                END Install;

                PROCEDURE Init;
                VAR
                     f: Factory;
                BEGIN
                     NEW(f); fact := f;
                END Init;

           BEGIN
                Init;
(*1*)  END WBDevFoxPMFB.
```

B3: winBUGS MODEL for scenario 1

```
model{
     r~dlnorm(-0.8439701, 51.51879)
     q~dunif(0.0,1.0)
     B0~dunif(0.1, 1.0)
     K~dunif(4,50)
     Tau~dgamma(0.001,0.001)

     B[1]<-B0*K
     for( i in 2:N)
     {
          FData[((i-1)*2-1):((i-1)*2)] <- PragerPMFB(r,K,Catch[i-1],B[i-1])
          B[i]<-        max(FData[(i-1)*2-1],0.0001)
          Ft[i-1]<- max(FData[(i-1)*2],0.0001)
     }
     for( i in 1:(N-1))
     {
          CPUEmed[i]<-log(q*Catch[i]/Ft[i])
          CPUE[i]~dlnorm(CPUEmed[i],Tau)
      }
      Bcur<-B[N-1]
      Bmsy<-K/2
      Fmsy<-r/2
      MSY<-(r*K)/4
      F01<-0.45*r
      Fcur<-Catch[N-1]/B[N-1]
}
```

B4: winBUGS MODEL for scenario 5

```
model{
     r~dlnorm(-0.8439701, 51.51879)
```

```
    q~dunif(0.0,1.0)
    B0~dunif(0.1, 1.0)
    K~dunif(4,50)
    Tau~dgamma(0.001,0.001)

    B[1]<-B0*K
    for( i in 2:N)
    {
        FData[((i-1)*2-1):((i-1)*2)] <- FoxPMFB(r,K,Catch[i-1],B[i-1])
        B[i]<-     max(FData[(i-1)*2-1],0.0001)
        Ft[i-1]<- FData[(i-1)*2]

    }
    for( i in 1:(N-1))
    {
        CPUEmed[i]<-log(q*Catch[i]/Ft[i])
        CPUE[i]~dlnorm(CPUEmed[i],Tau)
     }
     Bcur<-B[N-1]
     Bmsy<-K/2.718282
     Fmsy<-r
     MSY<-(r*K)/2.718282
     F01<-0.78152*r
     Fcur<-Catch[N-1]/B[N-1]
}
```

Appendix C: The R code for scenario 1 as an example

```
 setwd("E:\\IOTC\\MyData")
   library(R2WinBUGS)
   RData<-read.table("IOTCABLCatchData2.txt",header=T)
   BE<-(1980-1950+1):(2012-1950+1)
   Catch0<-RData[BE,"Total"]
   CPUETW0<- RData[BE,"CPUE_TW3"]
   Catch<-Catch0/max(Catch0)
   CPUETW<- CPUETW0/max(CPUETW0,na.rm =TRUE)
   N<-length(BE)+1
   params<-c("r","q","B0","K","Ft")
   bugsdir<- "C:/ WinBUGS14"
   modelfile="PragerModel8.txt"
   params<-c("r","q","B0","K","Ft","B","Tau")
   inits <- function(){
          list(r=rlnorm(1, -0.8439701, 0.1393212),q=0.4,B0=runif(1,0.9,1.0),K=runif(1,5,20),Tau=sd(CPUETW,na.rm =TRUE))
   }
   dat<-list(N=N,Catch=Catch,CPUE=CPUETW)
RBMPrager01T0.43<-bugs(dat,inits,params,model.file=modelfile,n.chains=3,n.iter=350000,n.burnin=150000,n.thin=75,bugs.directory=bugsdi
r,debug=F)
save(RBMPrager01T0.43,file="RBMPrager01T0.43.RData")
```