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Stock assessment of Indian Ocean blue shark (*Prionace glauca*) using Bayesian Pella-Tomlinson production model

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Summary

Pella-Tomlinson production model (PTPM) is a flexible production model that incorporates different hypotheses of density-dependence with a shape parameter. Given the time-series of catch, PTPM is fit only to abundance index data, which makes it useful in fisheries where age- or length-composition data are not available. In this study, we applied Bayesian approach to develop a PTPM for Indian Ocean blue shark (*Prionace glauca*)and used demographic analysis to inform prior information for key parameters. Matrix population model was used to derive informative prior distributions for the intrinsic growth rate (γ) and the shape parameter (p) of the PTPM. Eleven scenarios were considered to cover the main uncertainties in biological assumptions and initial population depletions. The impacts of informative and no-informative priors for parameters were also investigated. The models were fit to five abundance indices derived from main longline fisheries. The results are sensitive to the choices of CPUE indices. Most of the scenarios suggest that, at the beginning of 2015, the Indian Ocean blue shark was safe (B_{curr}/B_{msy}>1.0, F_{curr}/F_{msy}<1.0). This study endeavored to incorporate life-history information in a production model based stock assessment. We suggest that this type of methods be further developed and widely applied to IOTC species with relatively poor age- or length-composition data.

1 Introduction

Blue shark(*Prionace glauca*) is the most widespread pelagic shark species in the ocean ecosystem (Camhi,2008). They are caught as bycatch in commercial longline and gillnet fisheries that target tunas and swordfish, and also caught in the artisanal and coastal longline fisheries(Mejuto,2005;Carlos,2013). In the Indian Ocean, Japan, Indonesia, Taiwan, China, Spain, and Portugal longliners take majority of blue shark catch in recent years(IOTC,2015).

Three methods were conducted in 2015 for Indian Ocean blue shark(IOBSH), including SS3 model(Rice, 2015), Bayesian state-space surplus model(Andrade, 2015) and stock reduction analysis(IOTC, 2015). In this study, we applied a Bayesian Pella-Tomlinson production model (PTPM) for the Indian Ocean blue shark. Demographic analysis was used to develop informative prior distributions for intrinsic growth rate (γ) and shape parameter (p) of the PTPM. Five abundance indices (i.e., standardized longline CPUEs from Japan, Spain, Taiwan, China, Portugal, and Indonesia) and a catch time series of 1980-2015 were used to fit the PTPM model. Different scenarios were considered to cover the main uncertainties in biological assumptions and initial population depletions.

2 Method

2.1 Catch and abundance indices

The annual catch data of blue shark estimated by IOTC for 1980-2015 was selected, considering there is little catch information prior to early 1980's. We used standardized longline CPUE from different fleets for 1992-2015as abundance indices, i.e., Japan (Yasuko,2016),EU, Spain(Fernández-Costa,2015), Taiwan, China(Tsai,2015), EU, Portugal(Coelho,2015) and Indonesia(Novianto,2015)(**Table 1**).

2.2 Model

The Pella-Tomlinson(1969) production model, further developed by Polacheck(1993), was used to assess the IO BSH. In addition to intrinsic growth rate (γ) and carrying capacity (K)estimated in traditional Schaefer production model, the Pella-Tomlinson model defines a parameter p describing population's density dependence effect:

$$B_1 = K * \varphi \qquad t = 1 \tag{1}$$

$$B_{t+1} = B_t + \frac{\gamma}{p} B_t \left(1 - \left(\frac{B_t}{K}\right)^p\right) - C_t t \geq 2 \tag{2}$$

WhereB_t is the biomass at the start of year t, C_t is the total catch during the year t and φ is the ratio between B_1 to K.

The parameter p describes the relationship between recruitment and population density (it returns to Schaefer production model if p =1). Usually the parameter p is difficult to be estimated; in this case we can translate B_{MSY}/K to p:

$$B_{\mathrm{MSY}}/K = (p+1)^{-\frac{1}{p}} \tag{3}$$

Relationship between predicted abundance index using the m CPUE series in t year($\hat{I}_{tm}$) and B_t can be described as follows:

$$\hat{I}_{tm} = q_m B_t e^{\varepsilon} \tag{4}$$

and q_m can be calculated by equation

$$ln(\,q_m) = \frac{\sum_t^n ln(I_{tm}/B_t)}{n}$$

(5)

Where q_m is the catchability coefficient from the m CPUE series,ε is observation error following normal distribution with mean 0 and variance σ, andI_{tm} is observed abundance index and n is the number of observations of the m CPUE series.

The likelihood function for the CPUE following lognormal distribution can be described as:

$$LL = -\frac{2}{n}[ln(2\pi) + 2\,ln(\hat{\sigma}) + 1] - \sum_t^n ln(\,I_{tm}) \tag{6}$$

$$\hat{\sigma}^2 = \sum_{t=1}^n \frac{(ln(I_{tm}) - ln(\hat{I}_{tm}))^2}{n} \tag{7}$$

According to Bayesian theory(Punt,2002),the posterior distribution for the PTPM parameters (r, K, p, φ) is:

$$P(r, K, p, \varphi|I_1, I_2 \ldots I_t) = P(r)P(K)P(p)P(\varphi)LL(I_1, I_2 \ldots I_t|r, K, p, \varphi) \tag{8}$$

We sampled the joint parameter distribution using Monte Carlo method and find the maximum likelihood by solver. Uniform distribution from 0 to 1 plus maximum likelihood was used to select 10,000 values of posterior distribution. The calculation was implemented with the R program.

2.3 Demographic analysis

According to Fowler(1988), a linear equation was used to calculate B_{MSY}/K based on parameters γ and T(Equation 9), which can be both estimated by demographic method.

$$B_{\mathrm{MSY}}/K \; = \; 0.633 \; - 0.187\ln(\gamma T) \tag{9}$$

Biological parameters used for estimating γ and T were listed in **Table 2**. The detailed description of the demographic method was described by Geng (2017).

2.4 Prior distributions

The joints prior distribution of key parameters γ and p were estimated by demographic analysis, as listed in **Table 3**.The informative prior of K is based on same assumption as Andrade(2015), assuming a lognormal distribution with mean of 300,000t and standard deviation of 0.4. A uniform log space from 40,000t to 4,000,000t was assumed to be non-informative prior distribution for K.

According to Catch-MSY method(Thorson *et al*,2013),the yield in the 1980 as the beginning year is smaller than the half of maximum catch during the history. Thus, a uniform distribution with the range from 0.5 to 0.9 was regarded as the prior distribution of φ for the Base-case model. In sensitive analysis we fixed it as 0.4, 0.6, 0.8 and 1.Prior distributions of φ and K in each scenario are shown in **Table4**. Scenarios 1 to 4 were used to test the influence of different initial population state. Base-case and Scenario 5 would analyze the difference of the informative and non-informative prior distribution of K. Scenarios 6 to 10 were used to do sensitive analysis based on various biological assumptions.

2.4 Projection

We chose Base-case, Scenario6 and Scenario 10 to be the main cases of deriving the stock status of IOBSH. A 10 year projection with the annual removal equal to yield in 2014 was conducted. All 10,000 posterior distributions were used to make projection in each case. Observation and process errors were not considered in the projection.

3 Results

3.1 Base-case and sensitive analysis

For the Base-case with Japan CPUE, median MSY was estimated at 34.87 kt, and median B_{2015}/B_{msy} and F_{2015}/F_{msy} was 1.62 and 0.55,respectively. The median posterior distribution for parameter γ in Scenario 6 and Scenario 9 (the two scenarios assumed with 2-year reproductive cycle) were the lowest in all cases, and both of them have most pessimistic results (**Table5**).

On the contrary, the Scenario 5, with a wider range of *K*, resulted in the most optimistic stock status with median MSY of 112.93(1000t).Most scenario resulted in current stock status neither overfished nor overfishing (B_{year}>= B_{msy} and F_{year}<= F_{msy}). Only the Scenarios 6 resulted in overfishing but not overfished (B_{year}>= B_{msy} and F_{year}>= F_{msy})(**Fig. 1**).

The prior distribution of key parameters γ and *p* were correlated to some extent. There were no significant changes in their correlation between prior and posterior distribution under same biological assumption in all cases (**Fig. 2**).

Sensitive analysis based on different biological assumptions indicated that (**Fig.3**), the values of posterior distribution of key parameter *γ* were all higher than the values of prior distribution (**Fig.3a,c,e**). On the contrary, the values of the posterior distribution of B_{MSY}/K (**Fig. 3b,d,f**) were lower than the values of prior distribution. Comparing with lognormal survivorship distribution, the triangular survivorship distribution led to smaller and narrower prior and posterior distributions for parameter *γ*. Scenarios 6 and 9 produced smaller MSY and higher *K* estimates than others(**Fig.3g,h**).

3.2 Impact of CPUE on stock assessment

Posterior and prior distributions of key parameter ($\gamma,K,p,B_1/K$) of the Base-case model from different CPUE time series are shown in **Fig. 4**. There was no obvious difference between prior and posterior distributions for these parameters except for *K*. Posterior distributions of *K* from different CPUE time series have the same trend, with the highest estimates from CPUEs of Spain and Taiwan, China.

Fitting model to the five CPUE series for the Base-case was shown in **Fig. 5**; and the Kobe plots of Base-case and Scenario 10 with more optimistic results were shown in **Fig. 6.** The Portugal and Japan CPUE series fit better than other series. Over all, the estimated biomass showed similar trends, i.e., recovering from 1980's to the end of 2000's and decreasing in recent years.

For Scenario 6, CPUE series from Portugal, Japan and Taiwan, China led to overfishing but not overfished and CPUE series from Indonesia led to the edge of overfished. For the Base-case, CPUE series from Japan and Taiwan, China led to overfishing, and CPUE series from Portugal and Indonesia led to overfishing stock status. Overall, the stock status derived from CPUE series of Spain were more optimistic than other. For Scenario 10, all case have been safe status.

3.3 Projection

Future projection for the Base-case model with all CPUE series except for EU, Spain and Japan indicated that if we keep fishing at2014 catch level (C_{2014}) or more, the probability of achieving the target (B_{year}>= B_{msy} and F_{year}<= F_{msy}) would be less than 50% (**Table. 6**).

In this study, Scenario 6 (**Table. 7**)and 10 (**Table. 8**)were also used for projection with Kobe II Strategy Matrix. In Scenario 6 CPUE series of Portugal and Indonesia lead to less than 30% of probability for reaching the goal even if would have fished at 0.6 times of C_{2014} in the future 10 years.

Under CPUE series of Taiwan, China, the Scenario 10 using 1.4 times of 2014 catch will lead to a probability of 75% achieving the target (B_{year}>= B_{msy} and F_{year}<= F_{msy}) during the future 10 years(2016-2025). Under CPUE series of Portugal and Indonesia, keep fishing at the C_{2014}level would lead to more than 50% of probability of achieving the target. If we keep fishing at catch level of 0.6 times of C_{2014}, the stock will be in status within the target level with probability of higher than 75%, no matter which CPUE series was selected.

4. Discussion

Bayesian production model relies on catch and abundance index. In this study, except for the index from Portugal longline, the other indices couldn't result in good fitting. The main reason may come from difference between the continued increases of catch and varied trends of CPUE index. It would be more difficult to fit model when we already had made informative prior of parameters. However, this method could be used to select the most reasonable catch and index series, if biological information is reliably estimated.

Comparing to other parameters, informative prior distribution of *K* had a bigger influence on applying Bayesian production model for IOBSH. It tends to get optimistic stock status when we assumed higher prior value for ***K*.** With the improving in the estimates of biological parameters and catch data reconstruction, the assessment of IOBSH using Bayesian production model will be improved. Considering blue shark is a bycatch species with high uncertainty in the historical data, precautionary catch limit should be suggested to conserve the population.

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Table 1 Catch and abundance index data for the Indian Ocean blue shark assessment model

Group	Time Series	Source
Catch	1980-2015	IOTC database
Standardized CPUE	1992-2015	**Japan longline**
	2001-2015	**EU, Spain longline**
	2004-2015	**Taiwan, China longline**
	2000-2015	**EU, Portugal longline**
	2005-2015	**Indonesia longline**

Table 2 Biological information for demographic analysis of Indian Ocean blue shark

Parameter	Definition	Unit	Estimate	Range		Reference
Growth						
L_∞	Asymptotic length	cm, FL	258	255	261	
K	Growth coefficient	year^{-1}	0.161	0.158	0.164	Rabehagasoa *et al*.(2014)
t_0	Age at zero length	year	-0.89	-0.92	-0.86	
t_{max}	Longevity	year	$t_{max} = 5(\ln 2)/k$			Rice *et al*. (2014)
W-L	Weight at length	Kg-FL	$W = 0.835 \times 10^{-5} \times FL^{2.972}$			Romanov *et al*.(2009)
Reproduction						
t_{mat}	Maturity at age	year	U [5,7]			Pratt(1979)
LS 1	Litter size	pups	*LS*=-91.97+0.61FL			Mejuto *et al*.(2005)
LS 2			U [36.7,37.5]			Castro *et al*.(1995)
RLC 1	Reproductive length cycle	year	RLC=1			Nakano *et al*.(2008)
RLC 2	Reproductive length cycle	year	RLC=2			Nakano *et al*.(2008)

Notice: U[5,7] is uniform distribution from 5 to 7.

Table 3 Different biological assumptions for Indian Ocean blue shark

Biological assumptions	Fecundity	RLC	Survivorship distribution	γ_Median	γ_CV	B_{MSY}/K_Median	B_{MSY}/K_CV
A1	*LS* 1	*RLC* 1	Triangular	0.22	11.43	0.46	4.02
A2	*LS* 1	*RLC* 2		0.15	15.14	0.52	5.09
A3	*LS* 2	*RLC* 1		0.27	18.65	0.45	4.57
A4	*LS* 1	*RLC* 1	Lognormal	0.24	18.80	0.45	8.43
A5	*LS* 1	*RLC* 2		0.18	25.17	0.50	10.34
A6	*LS* 2	*RLC* 1		0.29	24.42	0.44	8.47

Table4 Scenario configurations for φ

Scenario	Biological Assumptions	φ	K
Base-case	**A1**	**φ~U[0.5-0.9]**	**ln(K)~Logn[300,0.4]**
Scenario1	A1	Fix(1.0)	ln(K)~Logn[300,0.4]
Scenario2		Fix(0.8)	
Scenario3		Fix(0.6)	
Scenario4		Fix(0.4)	
Scenario5	A1	φ~U[0.5-0.9]	ln(K)~U[ln40, ln4000]
Scenario6	A2	φ~U[0.5-0.9]	ln(K)~Logn[300,0.4]
Scenario7	A3		
Scenario8	A4		
Scenario9	A5		
Scenario10	**A6**		

Notice: Logn[300,0.4] is lognormal distribution with mean of 300 and standard deviation of 0.4.

Table 5 Median of the predicted posterior distributions of parameters and assessment result, based on Japan CPUE(1993-2015)

Parameters and reference points	Base-case	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6	Scenario7	Scenario8	Scenario9	Scenario10
γ	0.23	0.23	0.23	0.22	0.22	0.22	0.16	0.30	0.25	0.18	0.32
p	0.63	0.62	0.63	0.63	0.64	0.63	1.23	0.56	0.51	0.99	0.44
φ	0.67	1.00	0.80	0.60	0.40	0.68	0.63	0.69	0.68	0.65	0.69
K (1000t)	560.63	548.10	552.32	555.75	549.13	1859.75	643.26	497.96	532.78	606.46	482.38
MSY (1000t)	34.87	34.61	34.65	34.32	33.54	112.93	23.23	41.49	37.82	26.40	45.46
B_{msy} (1000t)	258.62	253.11	254.37	256.95	255.33	859.80	338.36	226.87	240.24	307.52	213.31
B_{2015} (1000t)	419.93	406.87	412.14	413.76	405.02	1724.51	450.16	383.85	403.91	431.49	377.91
C_{2015}/MSY	0.86	0.86	0.86	0.87	0.89	0.26	1.29	0.72	0.79	1.13	0.66
B_{2015}/K	0.75	0.74	0.75	0.74	0.74	0.93	0.70	0.77	0.76	0.71	0.79
B_{2015}/B_{msy}	1.62	1.61	1.61	1.61	1.59	1.99	1.33	1.71	1.68	1.41	1.78
F_{2015}	0.07	0.08	0.08	0.08	0.08	0.02	0.07	0.08	0.08	0.07	0.08
F_{msy}	0.14	0.14	0.14	0.14	0.13	0.13	0.07	0.19	0.16	0.09	0.22
F_{2015}/F_{msy}	0.55	0.56	0.56	0.56	0.58	0.13	1.00	0.44	0.49	0.83	0.39

Table 6 Kobe II Strategy Matrix (K2SM). Probability of achieving the goal of B_{year}>= B_{msy} and F_{year}<= F_{msy} for each year under constant catch scenarios based on Base-case. Red corresponds to 0-39%, yellow 40-60%, green >60%.

CPUE series	Catch	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Japan	C_{2014}*1.4	78.98	76.30	74.20	72.13	70.17	68.58	67.01	65.59	64.31	62.89
	C_{2014}*1.2	85.00	83.03	81.44	80.02	78.53	77.16	75.88	74.82	73.94	72.96
	C_{2014}*1.0	90.00	88.93	88.12	87.16	86.29	85.39	84.34	83.62	82.90	82.22
	C_{2014}*0.8	93.92	93.48	93.07	92.61	92.19	91.82	91.38	90.95	90.60	90.21
	C_{2014}*0.6	96.71	96.50	96.35	96.24	96.11	95.93	95.84	95.67	95.60	95.47
Spain	C_{2014}*1.4	89.88	87.76	85.68	83.64	81.70	80.01	78.30	76.66	75.33	73.87
	C_{2014}*1.2	94.29	92.95	91.82	90.81	89.58	88.39	87.43	86.37	85.46	84.44
	C_{2014}*1.0	97.24	96.75	96.18	95.74	95.11	94.53	93.97	93.40	92.84	92.52
	C_{2014}*0.8	98.88	98.63	98.38	98.20	98.03	97.90	97.78	97.66	97.48	97.32
	C_{2014}*0.6	99.64	99.60	99.57	99.55	99.51	99.46	99.45	99.44	99.41	99.38
Taiwan, China	C_{2014}*1.4	64.77	62.22	59.62	57.26	55.19	53.36	51.57	50.05	48.68	47.48
	C_{2014}*1.2	72.19	69.71	67.71	65.93	64.28	62.91	61.62	60.36	59.31	58.27
	C_{2014}*1.0	78.87	77.29	75.97	74.77	73.73	72.67	71.64	70.51	69.43	68.69
	C_{2014}*0.8	85.12	84.25	83.54	82.94	82.35	81.63	81.00	80.34	79.85	79.17
	C_{2014}*0.6	90.34	89.96	89.60	89.30	88.99	88.71	88.46	88.26	88.10	87.93
Portugal	C_{2014}*1.4	26.19	24.34	22.66	21.19	20.11	19.18	18.35	17.51	16.95	16.35
	C_{2014}*1.2	31.31	29.65	28.11	26.78	25.79	24.80	24.03	23.14	22.50	21.84
	C_{2014}*1.0	37.98	36.40	35.11	33.89	32.64	31.52	30.85	30.11	29.46	28.90
	C_{2014}*0.8	44.98	43.82	42.89	42.05	41.32	40.54	39.90	39.26	38.72	38.25
	C_{2014}*0.6	53.70	52.99	52.42	51.94	51.42	51.04	50.70	50.26	49.93	49.66
Indonesia	C_{2014}*1.4	27.72	25.44	23.94	22.42	21.14	19.92	18.96	18.08	17.39	16.77
	C_{2014}*1.2	33.55	31.67	30.04	28.55	27.14	26.01	25.08	24.44	23.75	23.06
	C_{2014}*1.0	40.55	38.95	37.20	35.85	34.71	33.94	32.94	32.23	31.50	30.86
	C_{2014}*0.8	47.64	46.52	45.44	44.43	43.72	43.02	42.36	41.71	41.22	40.82

	C_{2014}*0.6	55.38	54.85	54.34	53.88	53.38	53.07	52.76	52.47	52.10	51.80

Table 7 Kobe II Strategy Matrix (K2SM). Probability of achieving the goal of B_{year}>= B_{msy} and F_{year}<= F_{msy} for each year under constant catch scenariosbased on Scenario 6. Red corresponds to 0-39%, yellow 40-60%, green >60%.

CPUE series	Catch	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Japan	C_{2014}*1.4	28.34	26.28	24.5	22.87	21.27	20.1	18.96	18.11	17.39	16.62
	C_{2014}*1.2	36.47	34.64	32.94	31.22	29.61	28.39	27.14	26.12	25.1	24.29
	C_{2014}*1.0	45.86	44.2	42.54	40.9	39.66	38.39	37.26	36.35	35.41	34.65
	C_{2014}*0.8	56.09	54.77	53.56	52.33	51.22	50.25	49.31	48.46	47.69	46.85
	C_{2014}*0.6	67.31	66.33	65.42	64.68	63.95	63.22	62.39	61.76	61.12	60.69
Spain	C_{2014}*1.4	54.54	51.33	48.42	45.74	43.52	41.85	40.06	38.47	37.05	35.7
	C_{2014}*1.2	65.1	62.48	60.41	57.98	55.94	54.34	52.61	50.96	49.5	48.17
	C_{2014}*1.0	75.09	73.22	71.64	70	68.6	67.33	66.02	64.87	63.8	62.7
	C_{2014}*0.8	84.35	83.24	82.05	81.14	80.13	79.31	78.43	77.73	76.91	76.19
	C_{2014}*0.6	91.32	90.73	90.35	89.93	89.35	88.92	88.6	88.18	87.87	87.68
Taiwan, China	C_{2014}*1.4	30.33	28.46	26.63	25.4	24.15	23.09	22.19	21.34	20.45	19.76
	C_{2014}*1.2	37.41	35.72	34.05	32.62	31.48	30.23	29.24	28.23	27.44	26.59
	C_{2014}*1.0	45.85	44.06	42.7	41.48	40.27	39.18	38.08	37.23	36.36	35.77
	C_{2014}*0.8	55.01	53.76	52.63	51.59	50.72	49.72	48.97	48.14	47.38	46.77
	C_{2014}*0.6	65.15	64.42	63.54	62.93	62.31	61.75	61.15	60.57	60.08	59.55
Portugal	C_{2014}*1.4	2.66	2.15	1.84	1.56	1.36	1.19	1.06	0.94	0.86	0.76
	C_{2014}*1.2	5.06	4.22	3.64	3.19	2.81	2.51	2.29	2.07	1.89	1.72
	C_{2014}*1.0	9.01	8.12	7.21	6.65	6.08	5.63	5.2	4.81	4.45	4.16
	C_{2014}*0.8	15.65	14.63	13.7	12.96	12.26	11.67	11.12	10.52	9.9	9.52
	C_{2014}*0.6	24.7	24.02	23.25	22.4	21.83	21.21	20.64	20.23	19.82	19.42
Indonesia	C_{2014}*1.4	6.46	5.82	5.27	4.86	4.48	4.21	4.04	3.84	3.6	3.36
	C_{2014}*1.2	9	8.32	7.66	7.15	6.73	6.37	6	5.73	5.48	5.15
	C_{2014}*1.0	12.32	11.58	11.03	10.37	10.05	9.58	9.22	8.83	8.63	8.19
	C_{2014}*0.8	17.05	16.46	15.86	15.23	14.7	14.2	13.82	13.51	13.1	12.74

	C_{2014}*0.6	23.42	22.98	22.38	21.92	21.49	20.96	20.62	20.36	20.1	19.76

Table 8 Kobe II Strategy Matrix (K2SM). Probability of achieving the goal of B_{year}>= B_{msy} and F_{year}<= F_{msy} for each year under constant catch scenarios based on Scenario 10. Red corresponds to 0-39%, yellow 40-60%, green >60%.

CPUE series	Catch	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Japan	C_{2014}*1.4	92.89	91.39	90.18	89.36	88.24	86.97	86.23	85.42	84.61	84.05
	C_{2014}*1.2	95.09	94.5	93.97	93.24	92.57	91.91	91.19	90.79	90.47	89.95
	C_{2014}*1.0	96.97	96.56	96.26	95.86	95.69	95.35	95.06	94.84	94.7	94.5
	C_{2014}*0.8	98.24	98.17	98.05	97.91	97.75	97.71	97.6	97.42	97.3	97.21
	C_{2014}*0.6	98.98	98.96	98.92	98.89	98.89	98.89	98.88	98.86	98.83	98.79
Spain	C_{2014}*1.4	97.41	96.52	95.71	95.01	94.03	93.57	92.95	92.28	91.58	91.03
	C_{2014}*1.2	98.79	98.41	98	97.69	97.33	96.95	96.64	96.26	95.93	95.67
	C_{2014}*1.0	99.36	99.3	99.2	99.11	98.99	98.92	98.83	98.69	98.6	98.5
	C_{2014}*0.8	99.62	99.62	99.6	99.58	99.58	99.57	99.54	99.54	99.49	99.48
	C_{2014}*0.6	99.85	99.83	99.81	99.81	99.81	99.81	99.81	99.8	99.8	99.8
Taiwan, China	C_{2014}*1.4	86.17	84.26	82.45	80.88	79.73	78.51	77.59	76.59	75.7	75.04
	C_{2014}*1.2	89.87	88.77	87.86	86.66	85.71	84.84	84.05	83.49	82.83	82.27
	C_{2014}*1.0	93.36	92.68	91.92	91.33	90.76	90.33	89.85	89.55	89.25	88.94
	C_{2014}*0.8	95.69	95.53	95.37	95.16	94.94	94.78	94.66	94.47	94.17	94.05
	C_{2014}*0.6	97.42	97.38	97.32	97.28	97.2	97.13	97.08	97.05	97.02	97.01
Portugal	C_{2014}*1.4	52.31	49.86	47.65	45.71	44.13	43.18	42.12	41.21	40.32	39.57
	C_{2014}*1.2	58.16	55.92	54.06	52.88	51.86	50.65	49.58	48.74	48.09	47.28
	C_{2014}*1.0	64.39	62.94	61.86	60.74	59.7	58.83	57.99	57.21	56.63	56.08
	C_{2014}*0.8	70.76	70.03	69.42	68.85	68.35	67.77	67.22	66.71	66.36	66.14
	C_{2014}*0.6	76.58	76.37	76.27	76.17	76.07	76.06	76.03	75.92	75.86	75.75
Indonesia	C_{2014}*1.4	52.34	49.78	47.62	45.88	44.31	43.14	42.14	41.25	40.35	39.56
	C_{2014}*1.2	58.47	56.28	54.32	52.87	51.63	50.49	49.61	48.67	47.83	47.27
	C_{2014}*1.0	64.58	63.11	61.92	60.93	60.01	59.2	58.37	57.65	57.06	56.59
	C_{2014}*0.8	70.59	69.81	69.21	68.65	68.17	67.64	67.17	66.8	66.46	66.1

	C_{2014}*0.6	76.43	76.31	76.16	76.03	75.93	75.84	75.81	75.67	75.6	75.48

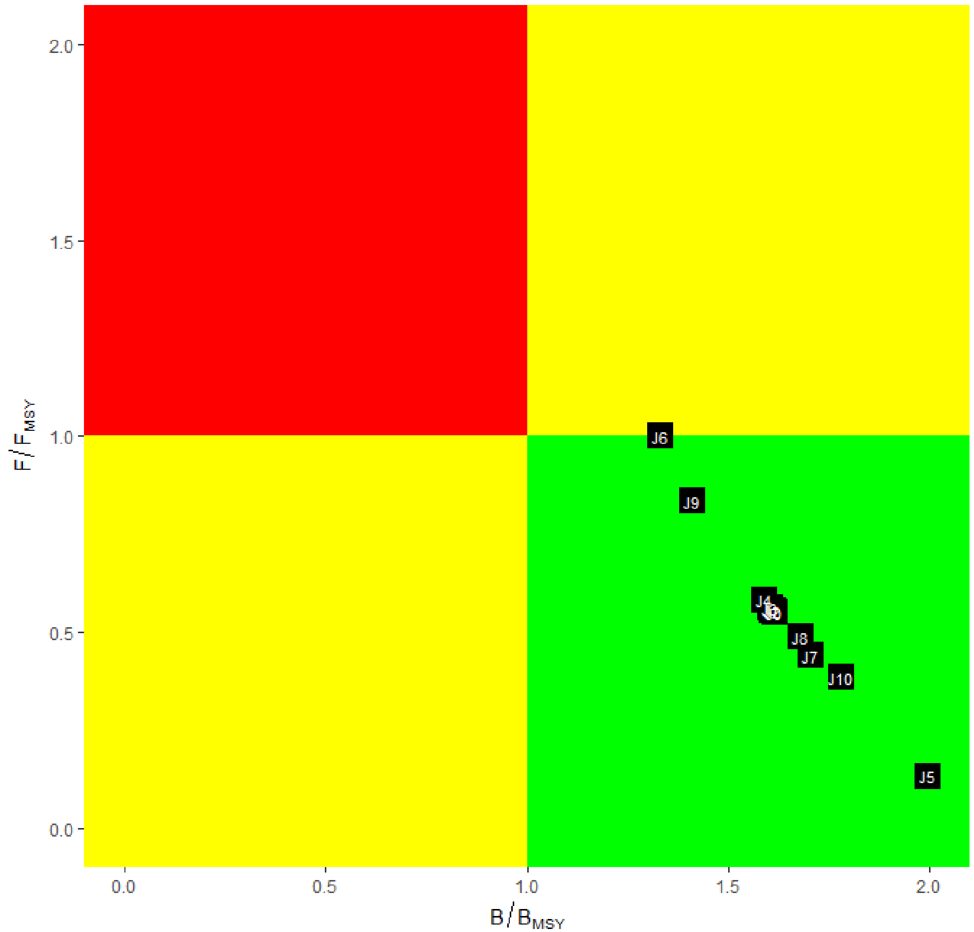


Figure 1 Kobe plot based on the median of B/Bmsy and F/Fmsy for Base-case (J0) and scenarios 1-10(J1-J10) with Japan CPUE.

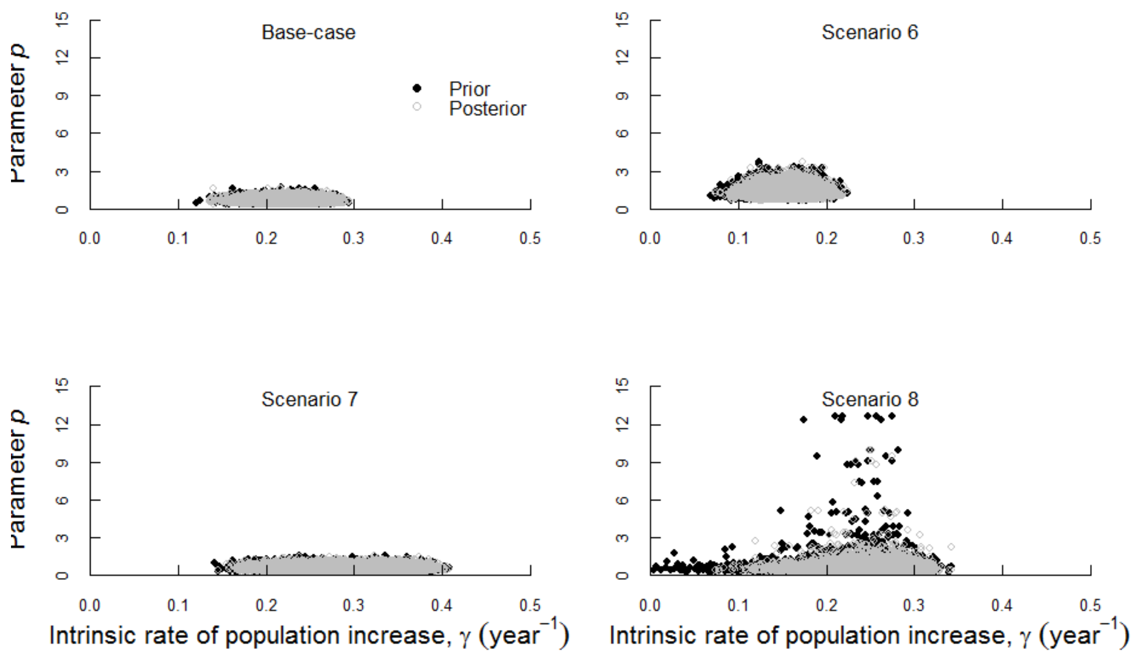
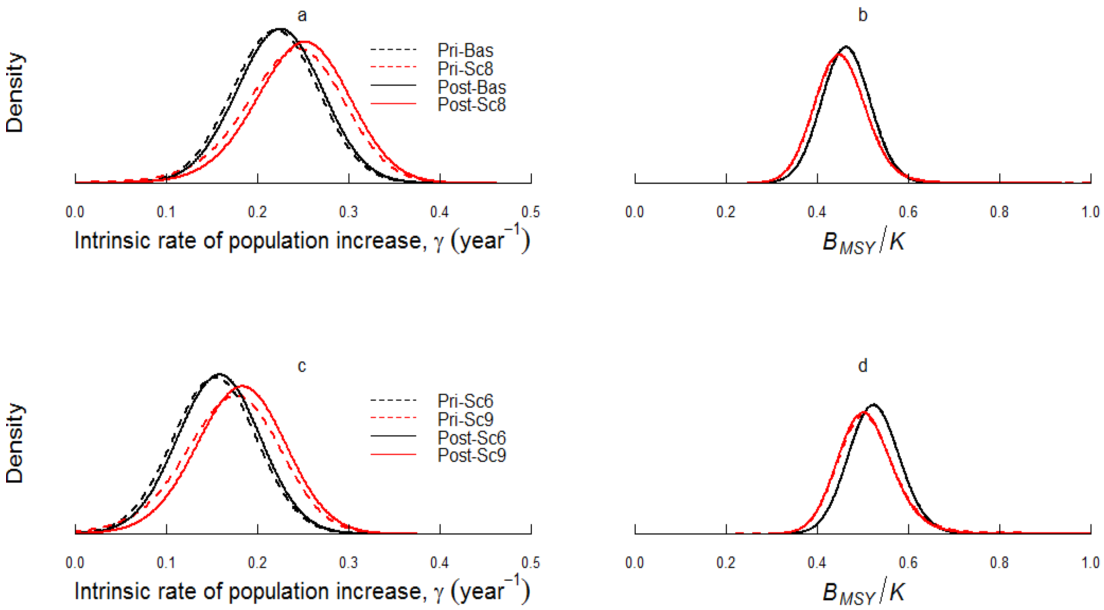


Figure 2 Comparing the correlation between the prior(black dot) and posterior(grey dot) distributions of key parameters γ and *p*under different biological assumptions(Base-case, Scenario 6-8) with the Japan CPUE.


a
b
c
d
Pri-Bas
Pri-Sc8
Post-Bas
Post-Sc8
Pri-Sc6
Pri-Sc9
Post-Sc6
Post-Sc9
Density
Density
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.2
0.4
0.6
0.8
1.0
Intrinsic rate of population increase, γ (year^{-1})
B_{MSY}/K
Intrinsic rate of population increase, γ (year^{-1})
B_{MSY}/K

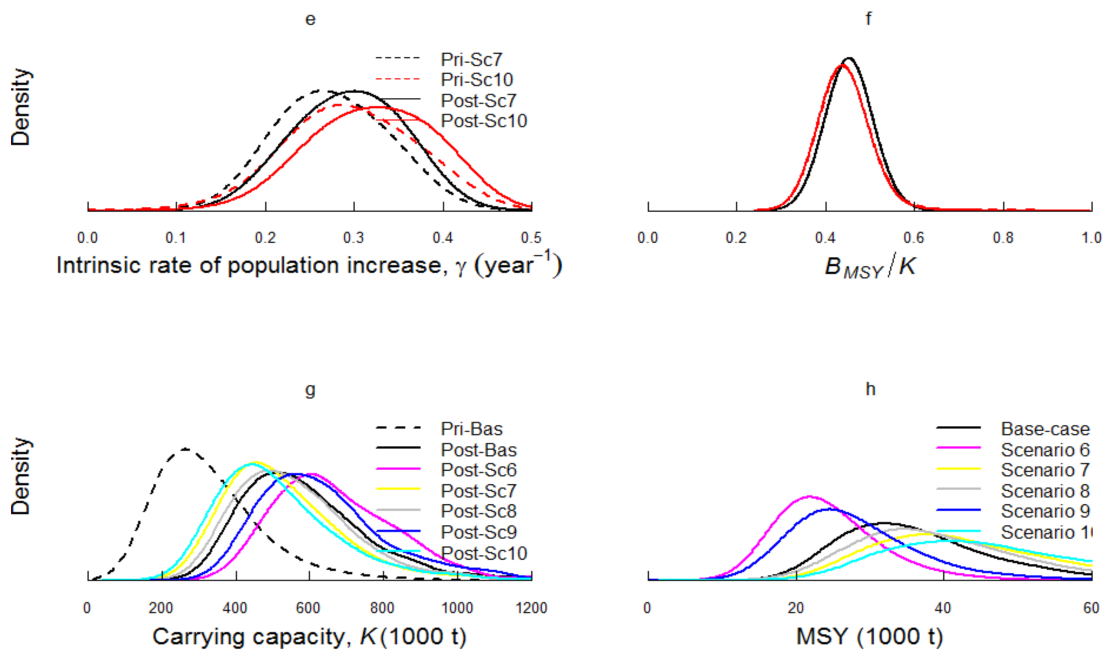


Figure 3 Prior(Pri, dash line) and posterior(Post, solid line) distribution of *γ, B_{MSY}/K, K* and MSY based on different biological assumptions (Base-case and Scenario 6-10), Pri-Bas is prior distribution for Base-case, Post-Sc8 is posterior distribution from scenario 8.Black line is Base-case and red line represents the others scenario in a-f; Black line: Base-case; purple line: scenario 6; yellow line:scenario 7; grey line:scenario 8;dark blue line and light blue line donate scenario 9 and 10 in g-h.

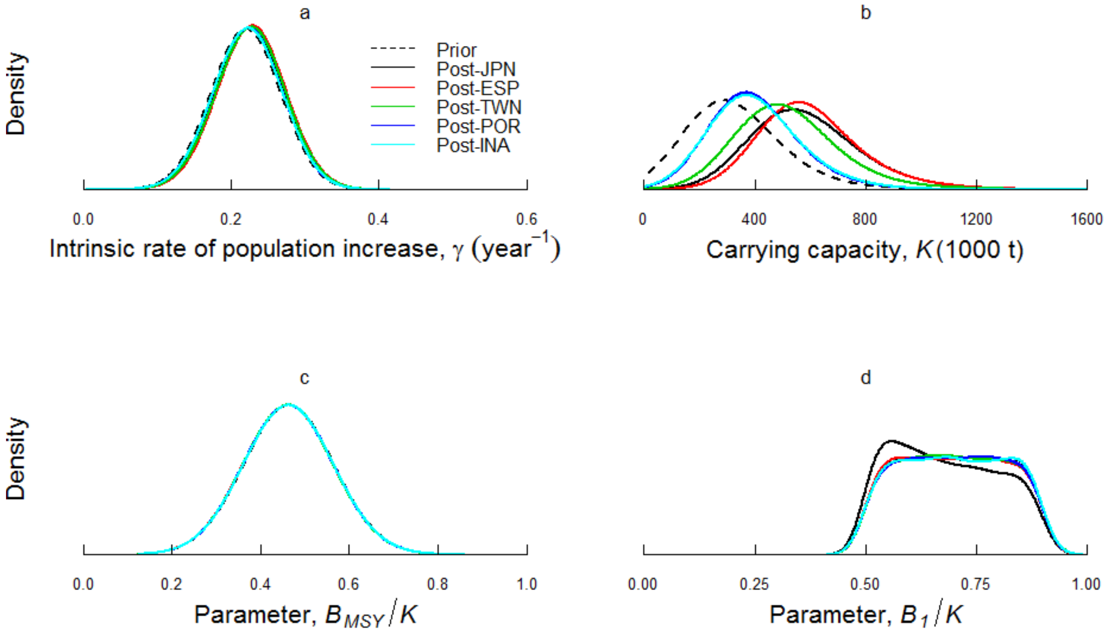


Figure 4.Comparisons of posterior distributions(solid line) of key parameter (γ,K,p,B_1/K) for the Base-case based on different CPUE indices (black line: Japan; red line: EU, Spain; green line: Taiwan, China; dark blue line:EU,Portugal; light blue: Indonesia).Dash line is prior distribution for the Base-case.

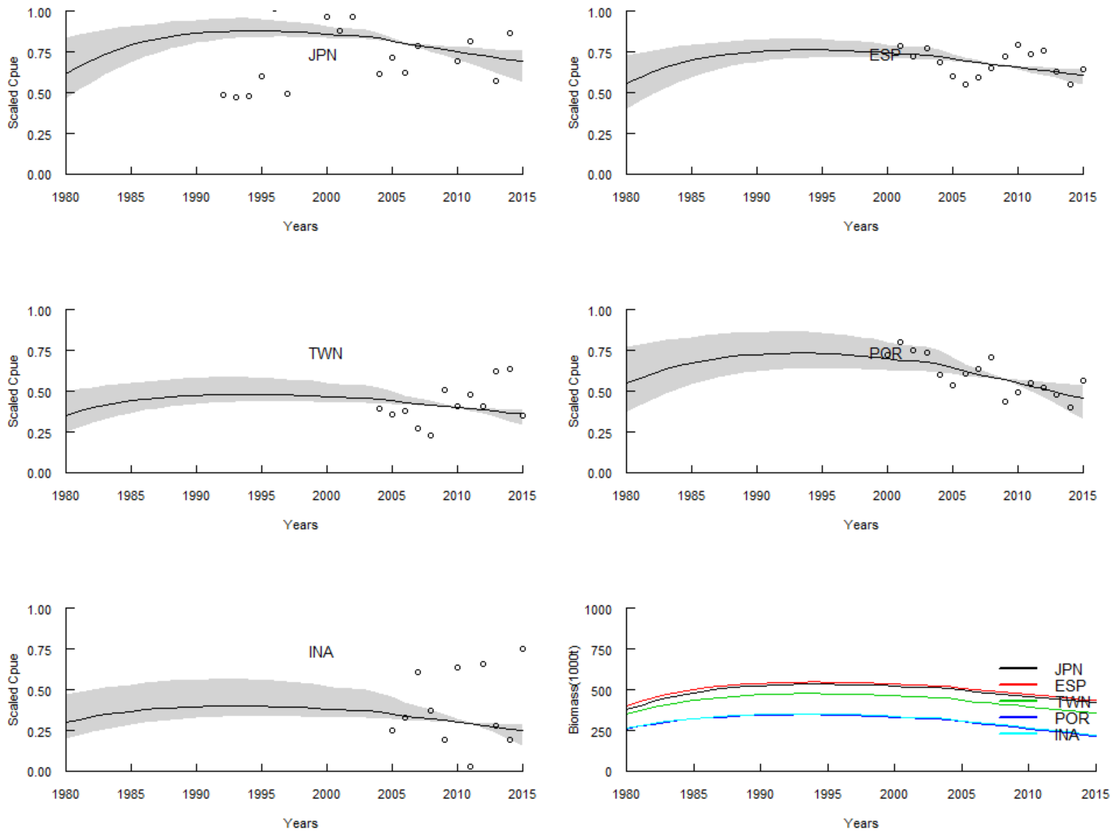


Figure 5.The median of predicted CPUE(thick line) with 95% confidence intervals(grey area) and observed CPUE(circle), and median of biomass for the Base-case with different CPUE series (JPN: Japan; SPN: EU, Spain; TWN: Taiwan, China; POR: EU, Portugal; IND: Indonesia)

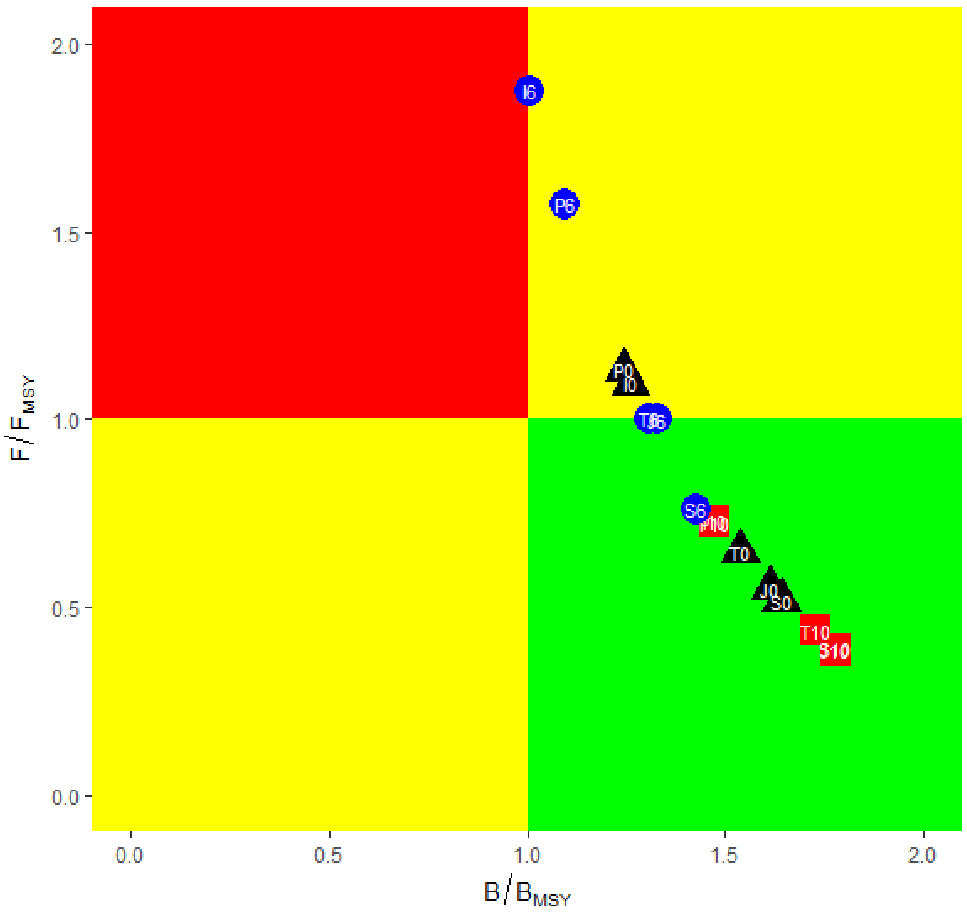


Figure 6 Kobe plot for the median of B/Bmsy and F/Fmsy under different CPUEs for the Base-case (black triangular, J0,S0,T0,P0 and I0), Scenario 6(blue circle, J6,S6,T6,P6 and I6) and Scenario 10(red square, J10, S10, T10, P10 and I10), where, J: Japan; S: EU, Spain; T: Taiwan, China; P: EU, Portugal; I: Indonesia.