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Developing state-space biomass dynamics model to assess the jumbo flying squid in Southeast Pacific Ocean

People's Republic of China

Updated stock assessment of the jumbo flying squid in the South-East Pacific

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Executive summary

The CPUEs of the Chinese squid-jigging fishery that represents Asia were standardized by the assumption of following a gamma distribution and used as relative abundance indices. Given the differences in operating methods, we used collected CPUE of Peru and Chile to increase the credibility of this study.

The stock assessment of the jumbo flying squid was based on the Bayesian state-space surplus production model. In the annual model, the stock has never been overfished and overfishing since 2012. Catch rates continued to be consistently below the maximum sustainable yield.

Of the seven environmental-dependent surplus production models, K model performed the best. Jumbo flying squid was extremely sensitive to climate change, in which it had a significant impact on its carrying capacity.

1. Introduction

The jumbo flying squid, *Dosidicus gigas*, is endemic to the eastern Pacific Ocean, with a distribution from California (37°N) to southern Chile (47°S), and to 140°W at the equator (Nigmatullin et al., 2001). *D. gigas* supports major fisheries in the coastal countries of Peru, Chile and Ecuador, while attracting industrial distant-water fishing fleets from Asia-Pacific countries (Morales-Bojórquez and Pacheco-Bedoya, 2016). Its semelparous reproduction, fast growth rate and short life span make individual sensitivity to environment (Arkhipkin et al., 2021), thus presenting a high inter-annual variability in recruitment and abundance (Waluda et al., 2006). Considering the biological significance of the model parameters, this study attempted to develop Bayesian state-space surplus production model and seven differently structured environmental dependent models to assess *D. gigas* throughout the Southeast Pacific Ocean.

2. Data

2.1 Catch and effort data

Total annual catch data of jumbo flying squid in the Southeast Pacific Ocean during 2012-2022 were derived from Food and Agriculture Organization (FAO) of United Nation (UN) database (www.fao.org/fishery/statistics/global-capture-production/query/en; accessed on 06/25/2024).

2.2 Abundance index data

(1) Peruvian fleets data

The abundance index (CPUE) defined as fishing yield per ship was directly from CALAMASUR.

(2) Chilean fleets data

In the Chilean EEZ, jumbo flying squid were caught as by-catch on multispecies trawlers and by direct small-scale hand-jig fishing. The standardized CPUE of trawl and jig fishery were both from CALAMASUR.

(3) Asian fleets data

The CPUE of the Asian fleet was represented by Chinese squid fishing fleet. The data were from China Distant Water Fisheries Association, with field for fishing time (date), fishing area (0.25° longitude ×0.25° latitude) and yield. Nominal CPUE was calculated by dividing catch by fishing days. Generalized Additive Model (GAM) is a common model for standardizing CPUE. The expression of GAM is as follows:

$$g(\mu_i) = \alpha + \sum f_i \times X_i + \varepsilon \quad (1)$$

α is the intercept. f_i is the related coefficient. ε is the error term which is assumed to follow statistical distribution. X_i is an independent variable including environmental factors (i.e. sea surface temperature (SST), concentration of chlorophyll-a (Chl_a), sea level anomaly (SLA), sea surface salinity (SSS) and Niño 1+2 index), spatial-temporal factors (i.e. year, month, longitude, latitude, region (Figure 1)) and interaction terms. Variance inflation factor (VIF<10) indicated no serious multicollinearity between explanatory variables (Table 1).

The assumptions of GAM was that CPUE follows the gamma distribution. For ease of modeling, the 0 value of nominal CPUE was removed.

Table 1. Variance inflation factor (VIF) among explanatory variables

Year	Month	Region	Niño 1+2 index	Latitude	Longitude	SST	SSS	Chl_a	SLA
1.589	2.076	4.563	1.606	7.744	5.140	4.837	1.823	1.162	1.680

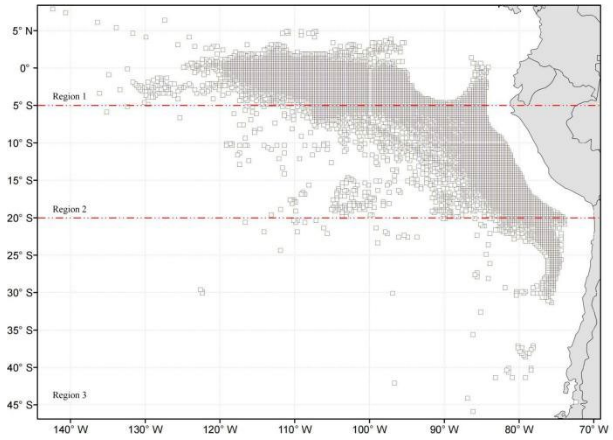


Figure 1. Distribution of regions

2.3 Environmental data

Environmental data came from remote sensing satellite dataset in National Oceanic and Atmospheric Administration (NOAA) database (https://oceanwatch.pifsc.noaa.gov/doc.html, https://origin.cpc.ncep.noaa.gov/data/indices/; accessed on 06/25/2024).

3. Model development

3.1 Description of Bayesian state-space surplus production model

A complete operational surplus production model consists of two parts, i.e. dynamic model which describe the recruitment, growth and mortality of the stock and observation model which relates observation (e.g. CPUE or abundance index by scientific survey) to the stock biomass (Hilborn et al., 1992).

Pella and Tomlinson considered an extension of Schaefer model:

$$B_{y+1} = (B_y + \frac{r}{s-1} B_y (1 - (\frac{B_y}{K})^{s-1} - C_{y,i}) e^{\mu_y} \quad (2)$$

where B_y is the biomass at the beginning of year y; C_y is catch in year y of i; μ_y is process error which follows normal distribution (e.g. μ_y~normal(0,τ^2)), r is the intrinsic growth rate and K is the capacity denoting the unexploited biomass size.

The form of observation model is as follows:

$$I_{y,i} = q_i B_y e^{\varepsilon_y} \quad (3)$$

where i is different fleets, in order of Peru, Asia, Chile_jig and Chile_trawl; $I_{y,i}$ is the index of abundance for year y, fleet i; q_i is catchability coefficient of fleet i ; ε_y is the observation error which follows normal distribution (e.g. ε_y~normal(0,σ^2)).

3.2 An environmental-dependent surplus production model

Three categories for key parameters (i.e., *r*, *K* and *s*) were determined by sea surface temperature anomaly (SSTA) in the Niño 1+2 area. Parameters *r*_El_Niño, *K*_El_Niño and *s*_El_Niño were used to denote *r*, *K* and *s* for certain years (months) when the SSTA was positive. Parameters *r*_La_Niña, *K*_La_Niña and *s*_La_Niña were used for the rest of the years (months) when the SSTA was negative (Figure 2). Seven models with different structures are as follow:

(1) K model: K1≠K2，r1=r2，s1=s2；

(2) r model: K1=K2，r1≠r2，s1=s2；

(3) s model: K1=K2，r1=r2，s1≠s2；

(4) Kr model: K1≠K2，r1≠r2，s1=s2；

(5) Ks model: K1≠K2，r1=r2，s1≠s2；

(6) rs model: K1=K2，r1≠r2，s1≠s2；

(7) Krs model: K1≠K2，r1≠r2，s1≠s2；

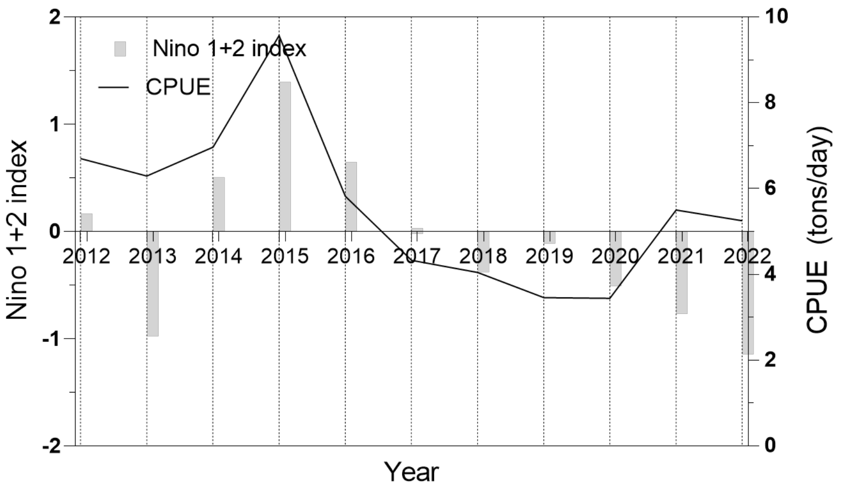


Figure 2 The annual SSTA of Niño 1+2 area and CPUE from year 2012 to 2022

3.3 Prior distribution

Setting appropriate prior distribution is primary in Bayesian paradigm. One base scenario and three sensitivity analysis scenarios were set based on varied prior distribution for traditional model and environmental dependent model. In all scenarios, the standard deviations of process and observation error follow inverse gamma distribution and the rest follow uniform distribution (Table 2 and 3).

Table 2. The prior distributions of parameters for traditional surplus production model

Parameter	Basic Scenario	Sensitivity scenario 1	Sensitivity scenario 2	Sensitivity scenario 3
r	uniform (0.1,4)	uniform (0.5,2)	uniform (0.1,4)	uniform (0.1,4)
K	uniform (1200,30000)	uniform (1200,30000)	uniform (1200,15000)	uniform (1200,30000)

q_1, q_2, q_3, q_4	uniform (0.0001,1)	uniform (0.0001,1)	uniform (0.0001,1)	uniform (0.0001,1)
s	uniform (0.1,5)	uniform (0.1,5)	uniform (0.1,5)	uniform (0.5,2.6)
B_{2012}/K	uniform (0.01,1)	uniform (0.01,1)	uniform (0.01,1)	uniform (0.01,1)
τ^2	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)
σ^2	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)

Table 3. The prior distributions of parameters for environmental-dependent model

Parameter	Basic Scenario	Sensitivity scenario 1	Sensitivity scenario 2	Sensitivity scenario 3
r_El_Niño r_La_Niña	uniform (0.1,4)	uniform (0.5,2)	uniform (0.1,4)	uniform (0.1,4)
K_El_Niño K_La_Niña	uniform (1200,30000)	uniform (1200,30000)	uniform (1200,15000)	uniform (1200,30000)
q_1, q_2, q_3, q_4	uniform (0.0001,1)	uniform (0.0001,1)	uniform (0.0001,1)	uniform (0.0001,1)
s_El_Niño s_La_Niña	uniform (0.1,5)	uniform (0.1,5)	uniform (0.1,5)	uniform (0.5,2.6)
B_{2012}/K	uniform (0.1,1)	uniform (0.1,1)	uniform (0.1,1)	uniform (0.1,1)
τ^2	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)
σ^2	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)	inverse gamma (0.001,0.001)

3.4 Posterior distribution and convergence test

Monte Carlo Markov Chain (MCMC) is used to estimate model parameters and biological reference points. The estimation process is carried out in Winbugs. Three chains are used and each chain calculates a total of 30,000 times. The first 10,000 times were discarded and the rest values are reserved once every 10 times. The initial value of each chain is shown in Table 4 and 5.

Convergence of the MCMC samples to the posterior distribution was checked by monitoring the trace of three chains of each parameter. Gelman and Rubin (1992) diagnostics was also examined.

Table 4. The initial value of different MCMC chains in traditional model

Parameter	K	r	q_1, q_2, q_3, q_4	B_{2012}/K	s	τ^2	σ^2
Chain 1	3000	0.6	0.02	0.5	0.6	0.1	0.1
Chain 2	6000	0.9	0.03	0.7	0.9	0.1	0.1
Chain 3	9000	1.2	0.04	1.0	1.2	0.1	0.1

Table 5. The initial value of different MCMC chains in environmental dependent model

Parameter	*K*_El_Niño	*K*_La_Niña	*r*_El_Niño	*r*_La_Niña	q_1, q_2, q_3, q_4	B_{2012}/K	*s*	τ^2	σ^2
Chain 1	3000	3000	0.6	0.6	0.02	0.5	0.6	0.1	0.1
Chain 2	6000	6000	0.9	0.9	0.03	0.7	0.9	0.1	0.1
Chain 3	9000	9000	1.2	1.2	0.04	1.0	1.2	0.1	0.1

3.5 Biological reference points estimation

The biological reference points are essential for figuring out the stock status and giving management advises. The biological references were calculated as follows:

$$B_{MSY} = Ks^{-1/(s-1)} \tag{4}$$

$$F_{MSY} = r/s \tag{5}$$

$$MSY = B_{MSY} \times F_{MSY} \tag{6}$$

4. Results

4.1 Generalized Additive Model

GAM analysis revealed that all the effects on CPUE were significant ($P<0.01$). The above variables were added to the model one by one and the optimal GAM which had a minimum AIC of 186431.1 incorporates all the significant variables (Table 6). Analysis of variance CPUE showed that year, month, region and Niño 1+2 index explained 9.99%, 5.61%, 2.7%, and 1.1%, respectively. The explained deviance of other factors was less than 1% (Table 7). The year effect was used as an abundance index in the stock assessment model. Nominal CPUE and standardized CPUE showed fluctuating trends, apparently opposite in 2012-2013, but both were highest in 2015 (Figure 3).

Table 6. Results of GAM selection

GAM	AIC	Deviance explained	R^2
CPUE~Year	193306.1	9.99%	0.098
CPUE~Year+Month	190213.8	15.6%	0.145
CPUE~Year+Month+Region	188686.9	18.3%	0.169
CPUE~Year+Month+Region+s(Niño)	188037.4	19.4%	0.175
CPUE~Year+Month+Region+s(Niño)+s(SSS)	187524.6	20.3%	0.19
CPUE~Year+Month+Region+s(Niño)+s(SSS)+s(Chl_a)	187520.8	20.4%	0.19
CPUE~Year+Month+Region+s(Niño)+s(SSS)+s(Chl_a)+s(SLA)	187316.9	20.7%	0.193

CPUE~Year+Month+Region+s(Niño)+s(SSS)+s(Chl_a)+s(SLA)+s(SST)	187019.9	21.2%	0.198
CPUE~Year+Month+Region+s(Niño)+s(SSS)+s(Chl_a)+s(SLA)+s(SST)+s(Latitude)	186629.1	21.8%	0.204
CPUE~Year+Month+Region+s(Niño)+s(SSS)+s(Chl_a)+s(SLA)+s(SST)+s(Latitude)+s(Longitude)	186431.1	22%	0.207

Table 7. Statistics results of the best GAM

	Year	Month	Region	Niño 1+2 index	Latitude	Longitude	SST	SSS	Chl_a	SLA
P	<0.01 ***	<0.01 ***	<0.01 ***	<0.01 ***	<0.01 ***	0.011 ***	<0.01 ***	<0.01 ***	<0.01 ***	<0.01 ***
df	10	11	2	8.892	8.606	2.677	8.429	7.213	7.668	3.823
Deviance explained	9.99%	5.61%	2.7%	1.1%	0.9%	0.1%	0.3%	0.5%	0.6%	0.2%

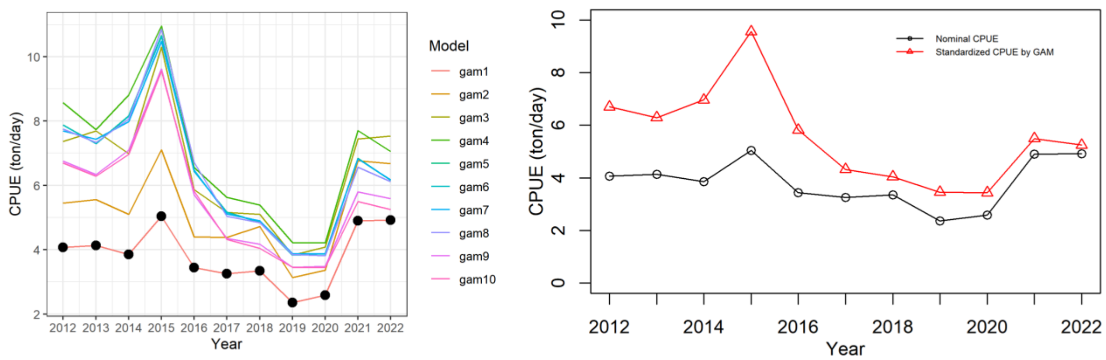


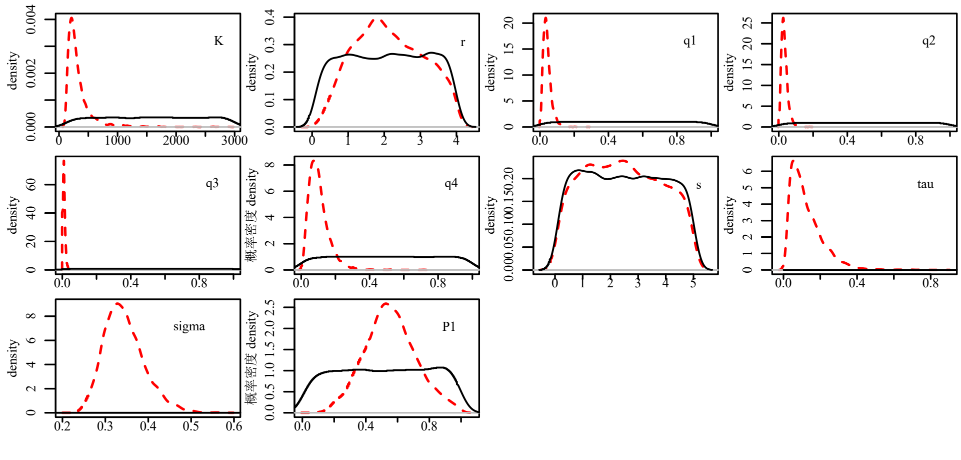
Figure 3. Nominal and standardized CPUE for jumbo flying squid

4.2 Estimates of parameters

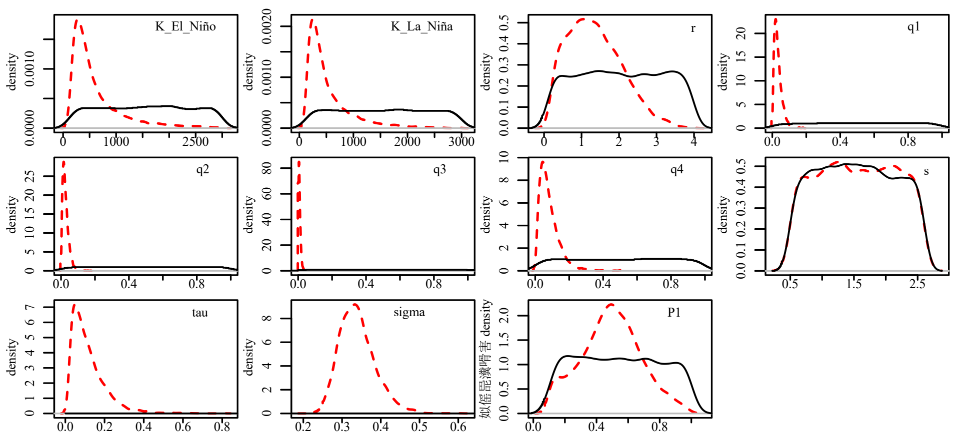
The significant difference between prior distribution and posterior distribution indicated that the data in the model provided sufficient information to dominate the form of posterior distribution in all scenarios (Figure 4 and 5).

The estimates of parameters for traditional surplus production model were shown in Table 8. For the base scenario, the mean and the median value of parameters r, K, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 2.14 and 2.07, 3.35 and 2.66 million tons, 0.042 and 0.038, 0.034 and 0.030, 0.012 and 0.010, 0.103 and 0.092, 2.47 and 2.43, 0.023 and 0.010, 0.121 and 0.115, 0.56 and 0.55, respectively. For the sensitivity analysis scenario 1, the mean and the median value of parameters r, K, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 1.34 and 1.38, 5.16 and 3.55 million tons, 0.038 and 0.034, 0.030 and 0.027, 0.010 and 0.009, 0.093 and 0.081, 1.87 and 1.59, 0.025 and 0.012, 0.119 and 0.113, 0.49 and 0.50, respectively. For the sensitivity analysis scenario 2, the mean and the median value of parameters r, K, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 2.01 and 1.95, 3.93 and 3.01 million tons, 0.042 and 0.037, 0.034 and 0.030, 0.012 and 0.010, 0.102 and 0.091, 2.44 and 2.41, 0.025 and 0.011, 0.121 and 0.116, 0.52 and 0.53, respectively. For the sensitivity analysis scenario 3, the mean and the median value of parameters r, K, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 1.85 and 1.77, 2.97 and 2.48 million tons, 0.051 and 0.045, 0.041 and 0.036, 0.014 and 0.012, 0.124 and 0.109, 1.57 and 1.57, 0.029 and 0.013, 0.123 and 0.118, 0.52 and 0.51, respectively.

According to results of the test, Ks model was non-convergent and K model with the minimum DIC was the best environmental dependent model (Table 9). The estimates of parameters for K model were shown in Table 10. For the base scenario, the mean and the median value of parameters K_El_Niño, K_La_Niña, r, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 7.77 and 5.01 million tons, 6.68 and 4.46 million tons, 1.61 and 1.48, 0.033 and 0.029, 0.026 and 0.023, 0.009 and 0.008, 0.079 and 0.070, 2.62 and 2.66, 0.023 and 0.009, 0.117 and 0.112, 0.45 and 0.47, respectively. For the sensitivity analysis scenario 1, the mean and the median value of parameters K_El_Niño, K_La_Niña, r, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 7.64 and 5.67 million tons, 6.59 and 4.94 million tons, 1.25 and 1.25, 0.029 and 0.025, 0.023 and 0.020, 0.008 and 0.007, 0.071 and 0.059, 2.35 and 2.23, 0.021 and 0.009, 0.115 and 0.110, 0.47 and 0.48, respectively. For the sensitivity analysis scenario 2, the mean and the median value of parameters K_El_Niño, K_La_Niña, r, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 5.50 and 4.50 million tons, 4.82 and 3.99 million tons, 1.75 and 1.63, 0.035 and 0.029, 0.028 and 0.024, 0.009 and 0.008, 0.084 and 0.071, 2.51 and 2.48, 0.021 and 0.009, 0.117 and 0.112, 0.49 and 0.50, respectively. For the sensitivity analysis scenario 3, the mean and the median value of parameters K_El_Niño, K_La_Niña, r, q_1, q_2, q_3, q_4, s, σ^2, τ^2 and B_{2012}/K were 6.13 and 4.40 million tons, 5.33 and 3.86 million tons, 1.36 and 1.29, 0.034 and 0.029, 0.027 and 0.023, 0.009 and 0.008, 0.083 and 0.068, 1.55 and 1.56, 0.022 and 0.009, 0.118 and 0.113, 0.49 and 0.49, respectively.



(a)



(d)

Figure 8. Prior and posterior distributions of parameters for environmental dependent model (a) base scenario; (b) sensitivity analysis scenario; the unit of K is 10^4 metric ton.

(The figure panels from left to right and from up to bottom respectively represent

K_El_Niño, *K_La_Niña*, r, q_1, q_2, q_3, q_4, s, σ^2, τ^2, and P_1)

Table 8 The estimates of parameters for traditional model

Scenario	Statistic	K (kt)	r	q_1	q_2	q_3	q_4	s	σ^2	τ^2	B_{2012}/K
Base scenario	mean	3346.76	2.14	0.042	0.034	0.012	0.103	2.47	0.023	0.121	0.56
	2.50%	1345.97	0.54	0.010	0.008	0.003	0.025	0.24	0.001	0.071	0.25
	25%	2014.00	1.42	0.026	0.021	0.007	0.062	1.32	0.004	0.097	0.45
	50%	2660.50	2.07	0.038	0.030	0.010	0.092	2.43	0.010	0.115	0.55
	75%	3754.00	2.88	0.053	0.043	0.015	0.130	3.59	0.028	0.138	0.66
	97.5%	10140.25	3.86	0.099	0.080	0.028	0.246	4.83	0.116	0.205	0.89
Sensitivity scenario 1	mean	5162.44	1.34	0.038	0.030	0.010	0.093	1.87	0.025	0.119	0.49
	2.50%	1675.00	0.57	0.009	0.007	0.003	0.023	0.19	0.001	0.070	0.07
	25%	2586.50	1.02	0.021	0.017	0.006	0.052	0.87	0.004	0.096	0.37
	50%	3552.50	1.38	0.034	0.027	0.009	0.081	1.59	0.012	0.113	0.50
	75%	5531.50	1.69	0.049	0.039	0.014	0.120	2.71	0.031	0.135	0.63
	97.5%	20997.20	1.97	0.093	0.073	0.026	0.231	4.67	0.117	0.203	0.88
Sensitivity scenario 2	mean	3932.48	2.01	0.042	0.034	0.012	0.102	2.44	0.025	0.121	0.52
	2.50%	1399.92	0.33	0.011	0.008	0.003	0.025	0.23	0.001	0.070	0.12
	25%	2154.00	1.23	0.025	0.020	0.007	0.060	1.28	0.004	0.097	0.41
	50%	3011.50	1.95	0.037	0.030	0.010	0.091	2.41	0.011	0.116	0.53
	75%	4643.25	2.76	0.053	0.043	0.015	0.130	3.56	0.028	0.139	0.65
	97.5%	12240.25	3.81	0.099	0.079	0.027	0.241	4.82	0.134	0.201	0.89
Sensitivity scenario 3	mean	2967.83	1.85	0.051	0.041	0.014	0.124	1.57	0.029	0.123	0.52
	2.50%	1285.97	0.54	0.012	0.010	0.003	0.029	0.56	0.001	0.071	0.19
	25%	1861.00	1.26	0.031	0.025	0.008	0.075	1.04	0.004	0.097	0.40
	50%	2475.00	1.77	0.045	0.036	0.012	0.109	1.57	0.013	0.118	0.51
	75%	3397.75	2.37	0.064	0.051	0.018	0.156	2.11	0.036	0.141	0.63
	97.5%	7865.07	3.56	0.126	0.098	0.034	0.307	2.55	0.150	0.209	0.89

Table 9 Results of statistics fitted to environmental dependent models

Model	K model	r model	s model	Kr model	Ks model	rs model	Krs model
DIC	6.141	123.523	91.921	49.945	34.522	109.176	57.141

Table 10 The estimates of parameters for environmental dependent model

Scenario	Statistic	K_El_Niño	K_La_Niña	s	q_1	q_2	q_3	q_4	s	σ^2	τ^2	B_{2012}/K
Base scenario	mean	7711.34	6679.61	1.61	0.033	0.026	0.009	0.079	2.62	0.023	0.117	0.45
	2.50%	1706.95	1541.95	0.25	0.005	0.004	0.001	0.013	0.24	0.001	0.069	0.11
	25%	3030.75	2705.00	0.89	0.018	0.014	0.005	0.043	1.40	0.003	0.094	0.28
	50%	5009.50	4455.00	1.48	0.029	0.023	0.008	0.070	2.66	0.009	0.112	0.47
	75%	10340.00	8909.25	2.22	0.043	0.034	0.012	0.104	3.81	0.025	0.134	0.61
	97.5%	25250.75	21680.50	3.61	0.084	0.067	0.023	0.205	4.88	0.124	0.194	0.85
Sensitivity	mean	7642.49	6590.62	1.25	0.029	0.023	0.008	0.071	2.35	0.021	0.115	0.47
scenario 1	2.50%	1979.85	1774.00	0.54	0.006	0.005	0.002	0.014	0.23	0.001	0.069	0.12
	25%	3694.00	3273.00	0.90	0.016	0.012	0.004	0.037	1.18	0.003	0.093	0.32
	50%	5669.50	4944.00	1.25	0.025	0.020	0.007	0.059	2.23	0.009	0.110	0.48
	75%	9445.00	8110.00	1.62	0.037	0.030	0.010	0.089	3.51	0.023	0.132	0.61
	97.5%	24510.50	20660.50	1.96	0.083	0.067	0.023	0.201	4.80	0.111	0.190	0.85
Sensitivity	mean	5496.54	4817.27	1.75	0.035	0.028	0.009	0.084	2.51	0.021	0.117	0.49
scenario 2	2.50%	1660.92	1486.92	0.32	0.008	0.006	0.002	0.018	0.23	0.001	0.069	0.13
	25%	2962.75	2647.00	1.01	0.019	0.015	0.005	0.045	1.33	0.003	0.094	0.35
	50%	4503.00	3987.50	1.63	0.029	0.024	0.008	0.071	2.48	0.009	0.112	0.50
	75%	7336.00	6345.00	2.42	0.045	0.035	0.012	0.107	3.67	0.024	0.134	0.63
	97.5%	13530.00	11820.25	3.70	0.093	0.073	0.026	0.228	4.86	0.121	0.198	0.88

Sensitivity	mean	6128.72	5327.92	1.36	0.034	0.027	0.009	0.083	1.55	0.022	0.118	0.49
scenario 3	2.50%	1634.95	1494.97	0.26	0.006	0.005	0.002	0.014	0.56	0.001	0.068	0.13
	25%	2851.00	2538.00	0.80	0.017	0.014	0.005	0.041	1.05	0.003	0.095	0.36
	50%	4395.50	3860.00	1.29	0.029	0.023	0.008	0.068	1.56	0.009	0.113	0.49
	75%	7528.00	6562.50	1.84	0.045	0.036	0.012	0.109	2.07	0.025	0.135	0.61
	97.5%	21150.25	17770.75	2.92	0.094	0.076	0.026	0.233	2.55	0.128	0.200	0.87

4.3 Biological reference points

Three biological reference points were estimated. The results from traditional model were shown in Table 11. For the base scenario, the mean and median value of MSY were 1.38 and 1.22 million tons. The mean and median value of F_{MSY} were 1.25 and 0.93. The mean and median value of B_{MSY} were 1.71 and 1.34 million tons. For the sensitivity analysis scenario 1, the mean and median value of MSY were 1.70 and 1.33 million tons. The mean and median value of F_{MSY} were 1.30 and 0.84. The mean and median value of B_{MSY} were 2.57 and 1.56 million tons. For the sensitivity analysis scenario 2, the mean and median value of MSY were 1.49 and 1.25 million tons. The mean and median value of F_{MSY} were 1.15 and 0.85. The mean and median value of B_{MSY} were 1.96 and 1.46 million tons. For the sensitivity analysis scenario 3, the mean and median value of MSY were 1.37 and 1.22 million tons. The mean and median value of F_{MSY} were 1.30 and 1.20. The mean and median value of B_{MSY} were 1.30 and 1.06 million tons.

The results from environmental dependent model were shown in Table 12. For the base scenario, the mean and median value of MSY_El_Niño and MSY_La_Niña were 1.97 and 1.55 million tons, 1.72 and 1.36 million tons, respectively. The mean and median value of F_{MSY} were 0.90 and 0.63. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 4.09 and 2.47 million tons, 3.54 and 2.19 million tons, respectively. For the sensitivity analysis scenario 1, the mean and median value of MSY_El_Niño and MSY_La_Niña were 2.01 and 1.63 million tons, 1.75 and 1.40 million tons, respectively. The mean and median value of F_{MSY} were 0.99 and 0.56. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 4.09 and 2.82 million tons, 3.52 and 2.46 million tons, respectively. For the sensitivity analysis scenario 2, the mean and median value of MSY_El_Niño and MSY_La_Niña were 1.81 and 1.52 million tons, 1.59 and 1.33 million tons, respectively. The mean and median value of F_{MSY} were 1.01 and 0.72. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 2.78 and 2.20 million tons, 2.44 and 1.94 million tons, respectively. For the sensitivity analysis scenario 3, the mean and median value of MSY_El_Niño and MSY_La_Niña were 1.85 and 1.49 million tons, 1.61 and 1.30 million tons, respectively. The mean and median value of F_{MSY} were 0.98 and 0.87. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 2.69 and 1.88 million tons, 2.34 and 1.66 million tons, respectively.

Table 11 The estimates of biological reference points for traditional model

Scenario	Statistic	MSY(kt)	F_{MSY}	B_{MSY}(kt)
Base scenario	mean	1384.68	1.245	1705.47
	2.50%	909.10	0.264	373.08
	25%	1071.00	0.668	917.77
	50%	1222.00	0.926	1341.00
	75%	1511.00	1.361	1949.25
	97.5%	2842.05	4.468	5584.22
	mean	1698.08	1.295	2566.58

	2.50%	899.28	0.225	308.56
Sensitivity	25%	1087.00	0.501	916.40
	50%	1325.00	0.835	1559.00
scenario 1	75%	1793.00	1.456	2838.50
	97.5%	5256.27	5.743	12470.00
	mean	1488.85	1.145	1962.34
	2.50%	899.88	0.262	409.85
Sensitivity	25%	1071.00	0.601	990.17
scenario 2	50%	1248.00	0.854	1460.00
	75%	1577.00	1.269	2322.50
	97.5%	3828.22	4.331	6957.15
	mean	1368.93	1.299	1293.72
	2.50%	915.49	0.408	499.49
Sensitivity	25%	1065.00	0.869	788.67
scenario 3	50%	1219.00	1.204	1062.00
	75%	1489.00	1.585	1502.25
	97.5%	2652.05	2.910	3569.62

Table 12 The estimates of biological reference points for environmental dependent model

Scenario	Statistic	EI_Niño			La_Niña		
		MSY	F_{MSY}	B_{MSY}	MSY	F_{MSY}	B_{MSY}
	mean	1974.00	0.897	4089.88	1718.01	0.897	3539.82
	2.50%	945.00	0.144	542.37	860.89	0.144	488.78
	25%	1232.75	0.380	1415.75	1082.00	0.380	1267.50
Base scenario	50%	1547.00	0.631	2471.00	1362.50	0.631	2188.00
	75%	2272.25	1.004	5552.25	1955.50	1.004	4764.75
	97.5%	5017.07	3.458	14841.50	4371.15	3.458	12860.75
	mean	2013.70	0.987	4090.30	1747.15	0.987	3519.63
Sensitivity	2.50%	952.88	0.178	444.18	871.30	0.178	397.18
	25%	1259.00	0.359	1476.00	1109.00	0.359	1306.75
scenario 1	50%	1629.00	0.556	2824.00	1403.50	0.556	2461.00
	75%	2331.25	1.056	5299.00	2004.50	1.056	4542.75
	97.5%	4999.20	4.680	15131.00	4366.17	4.680	12810.25
	mean	1812.92	1.006	2780.73	1588.55	1.006	2435.23
	2.50%	946.70	0.227	536.55	869.80	0.227	474.71
Sensitivity	25%	1219.00	0.474	1339.00	1085.00	0.474	1203.00
scenario 2	50%	1519.00	0.717	2196.50	1327.00	0.717	1941.00
	75%	2064.00	1.095	3711.00	1804.00	1.095	3226.25
	97.5%	4395.37	3.858	7834.00	3810.12	3.858	6914.07
	mean	1845.75	0.976	2690.02	1610.77	2338.22	1845.75
Sensitivity	2.50%	1200.00	0.542	1186.00	1062.00	1061.00	1200.00
scenario 3	25%	1486.00	0.868	1880.50	1298.50	1659.00	1486.00
	50%	2050.00	1.270	3248.25	1781.25	2856.00	2050.00

	75%	4980.07	2.440	9719.50	4209.22	8120.35	4980.07
	97.5%	1845.75	0.976	2690.02	1610.77	2338.22	1845.75

4.5 Stock status

The temporal trends of Bratio (B/B_{MSY}) and Fratio (F/F_{MSY}) in different scenarios showed similar patterns. According the Kobe plot, the stock being overfishing or overfished had never happened since 2012, and the probability of the stock being healthy in the terminal year in traditional model were 86.6%, 77.1%, 78.6% and 86.2% (Figure 6). The probability of the stock being healthy in the terminal year in environmental dependent model were 62.6%, 67%, 72% and 79.7% (Figure 7).

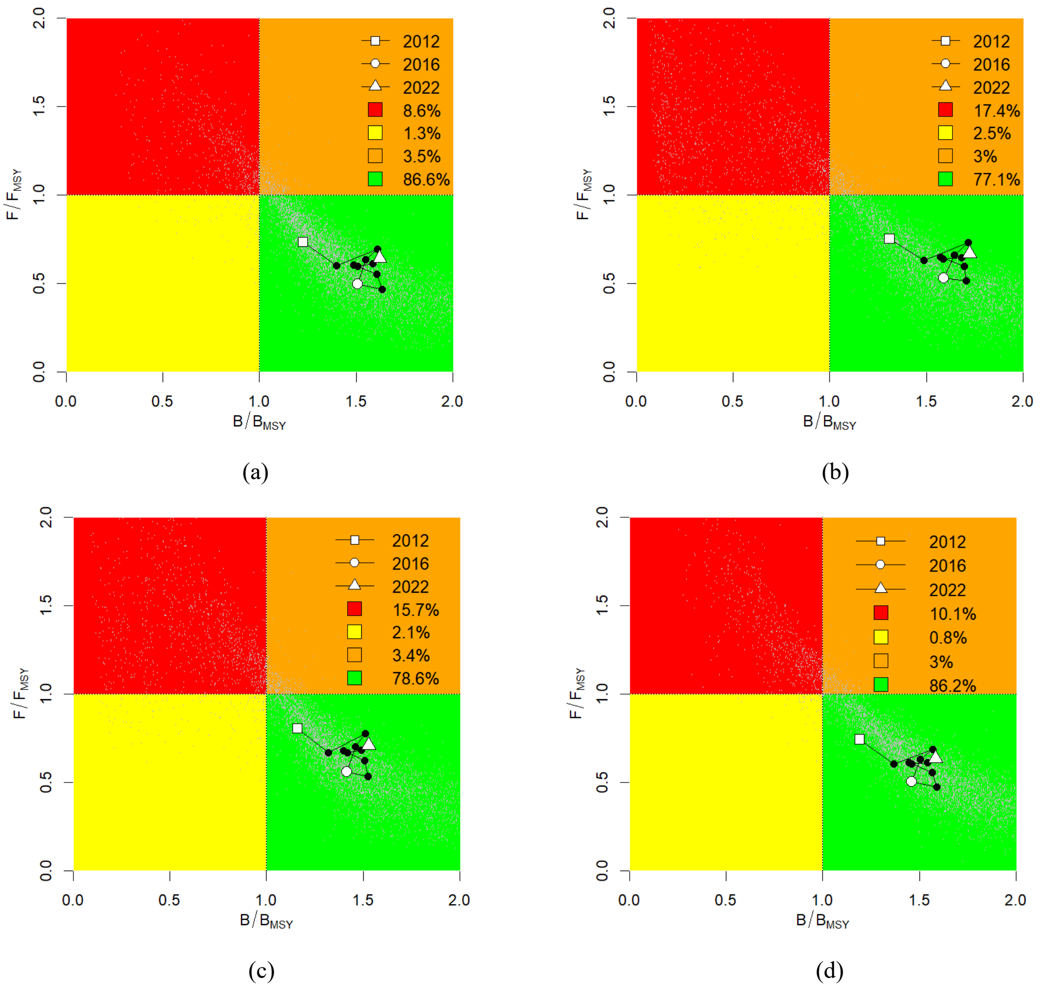


Figure 6. Kobe plot of traditional model, (a) base scenario, (b) sensitivity analysis scenario 1, (c) sensitivity analysis scenario 2, (d) sensitivity analysis scenario 3

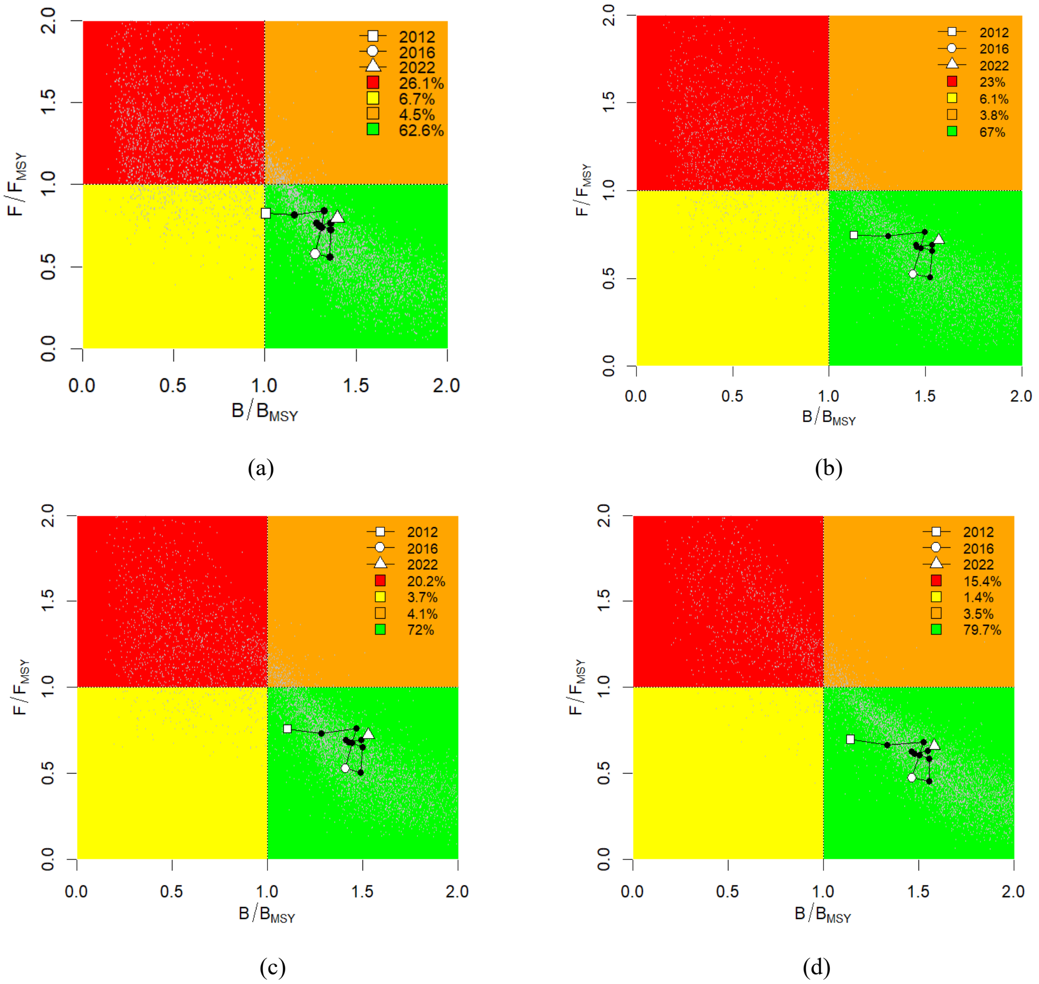


Figure 7. Kobe plot of environmental dependent model, (a) base scenario, (b) sensitivity analysis scenario 1, (c) sensitivity analysis scenario 2, (d) sensitivity analysis scenario 3

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