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

People's Republic of China

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

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Executive summary

The CPUEs of the Chinese squid-jigging fishery were standardized by the assumption of following a gamma distribution and used as relative abundance indices. Bayesian state-space surplus production models were employed to assess this stock from 2012 to 2021, taking into account annual and monthly data, as well as environmental conditions (El Niño and La Niña). Furthermore, we consider utilizing three different CPUEs in the assessment model due to the differences in operating methods and regions in Peru, Chile and China.

In the annual model, the stock has never been overfished and overfishing. In El Niño or La Niña years, K, MSY, and B_{MSY} increased, while the intrinsic rate of increase (r) decreased during El Niño conditions but increased during Niña years.

In the monthly model, stock biomass exceeded 0.3 B_{MSY} but fell below B_{MSY} in some months (mostly August-December during 2017-2021 except 2019). Fishing mortality remained much lower than F_{MSY} regardless of environmental impacts, indicating no overfishing. The cause of this result still needs to be further studied.

The fishing mortality rate set at F_{2021} (0.366~0.667) and 1.5$F_{2021\text{-}12}$ (0.046~0.073) were optimal for the future jumbo flying squid stock. In any given catch strategy, monthly biomass would rise and recover to B_{MSY}. There is uncertainty in the actual process of population dynamics, which can be addressed by calculating the biomass that takes into account environmental impacts based on predicted Oceanic Niño Index. In addition, short-term management decision for jumbo flying squid should attempt to set various levels of monthly fishing mortality based on life history characteristics.

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). It is one of the most abundant squids globally, harvested by domestic fleets from Chile and Peru, as well as Chinese industrial distant-water fishing fleets operating in the high seas (Morales-Bojórquez and Pacheco-Bedoya, 2016). Owing to the environmental sensitivity of jumbo flying squid, climatic phenomena at various spatial and temporal scales (e.g. El Niño and La Niña) have significant impacts on distribution and resource abundance in the short term (Taipe, et al., 2001; Waluda et al., 2006). In addition, jumbo flying squid are characterized by fast growth rate and short life span, which makes the assessment and management of their populations challenging. Refining the time step of the model may help to handle the above characteristics in the stock assessment (Arkhipkin, et al., 2021). In this report, we attempted to use catch and effort data from the Chinese, Peruvian and Chilean fleets to develop Bayesian state-space surplus production model and environmental dependent model for assessing the jumbo flying squid.

2. Data

2.1 Catch and effort data

Total annual catch data of jumbo flying squid in the Southeast Pacific Ocean during 2012-2021 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 06/01/2023). Monthly catch and effort for Chile and Peru were provided by CALAMASUR, and others are from the SPRFMO annual report.

2.2 Abundance index data

(1) Peruvian fleets data

The abundance index (CPUE) data was directly from CALAMASUR.

(2) Chilean fleets data

The CPUE was calculated as follows:

$$CPUE_{y,m} = Catch_{y,m} / \, Effort_{y,m} \qquad (1)$$

where $Catch_{y,m}$ is the total catch occurred in year y and month m. $Effort_{y,m}$ and $CPUE_{y,m}$ are the total fishing efforts (hauls) and CPUE, respectively.

(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 defined as the fishing yield per day, in units of tons per day. Generalized Additive Model (GAM) is a common model for standardizing CPUE. The expression of GAM is as follows:

$$g(\mu_i) = \alpha + \sum f_i \times X_i + \varepsilon \qquad (2)$$

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 the two types of GAM models were that log(CPUE) follows a normal distribution and CPUE follows a gamma distribution, respectively. For ease of modeling, the 0 value of nominal CPUE was removed.

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

Year	Month	Region	Nino 1+2 index	Latitude	Longitude	SST	SSS	Chl_a	SLA
1.59	2.08	4.56	1.61	7.69	5.11	4.83	1.81	1.16	1.68

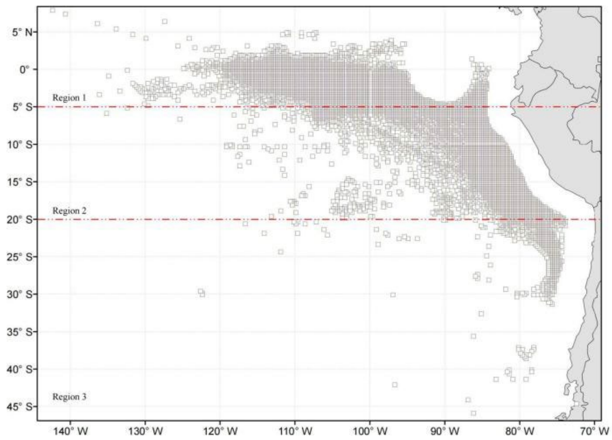


Figure 1. Distribution of regions

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 06/01/2023).

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:

$$B_{y+1} = (B_y + rB_y(1 - (\frac{B_y}{K})^s - C_{y,i})e^{\mu_y} \quad (3)$$

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. $\mu_y \sim normal(0,\sigma^2)$), r is the intrinsic growth rate and K is the capacity denoting the unexploited biomass size.

The form of observation model is as follows:

$$I_{y,i} = q_i B_y e^{\varepsilon_y} \quad (4)$$

where i is different fleets, in order of Asia, Peru and Chile; $I_{y,i}$ 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. $\varepsilon_y \sim normal(0,\tau^2)$).

In this study, year-based and month-based Bayesian state-space Pella and Tomlinson's surplus production model was chosen to describe the fishery dynamic of jumbo flying squid in Southeast Pacific.

3.2 An environmental-dependent surplus production model

Cross-correlation analysis of the Niño 1+2 index with CPUE showed a lag time of 4 months for impacts (Figure 2). Two categories for key parameters (i.e., r and K) were determined by sea surface temperature anomaly (SSTA) in the Niño 1+2 area. Parameters *r*_El_Niño and *K*_El_Niño were used to denote *r* and *K* for certain years (months) when the SSTA was positive. Parameters *r*_La_Niña and *K*_La_Niña were used for the rest of the years (months) when the SSTA was negative (Figure 3 and 4).

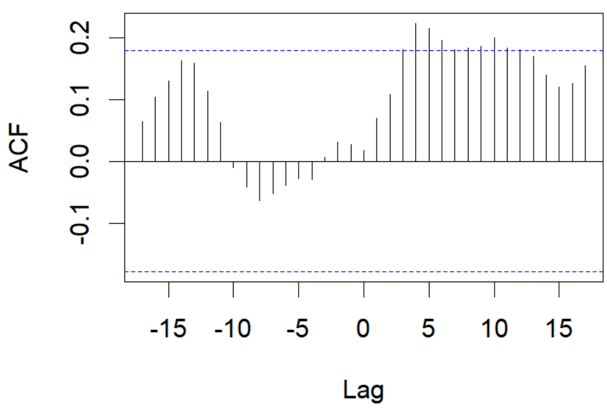


Figure 2 Cross correlation function study on Niño 1+2 index and CPUE

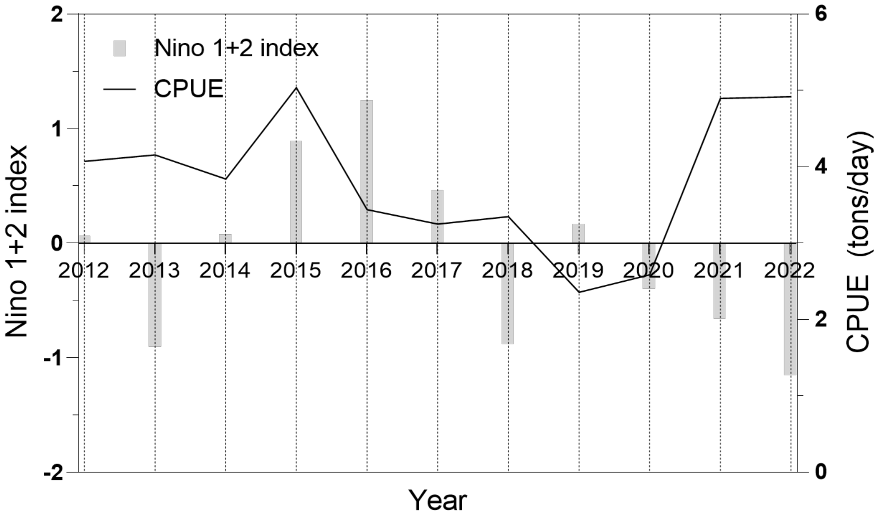


Figure 3 The annual SSTA of Niño 1+2 area and CPUE from year 2012 to 2022

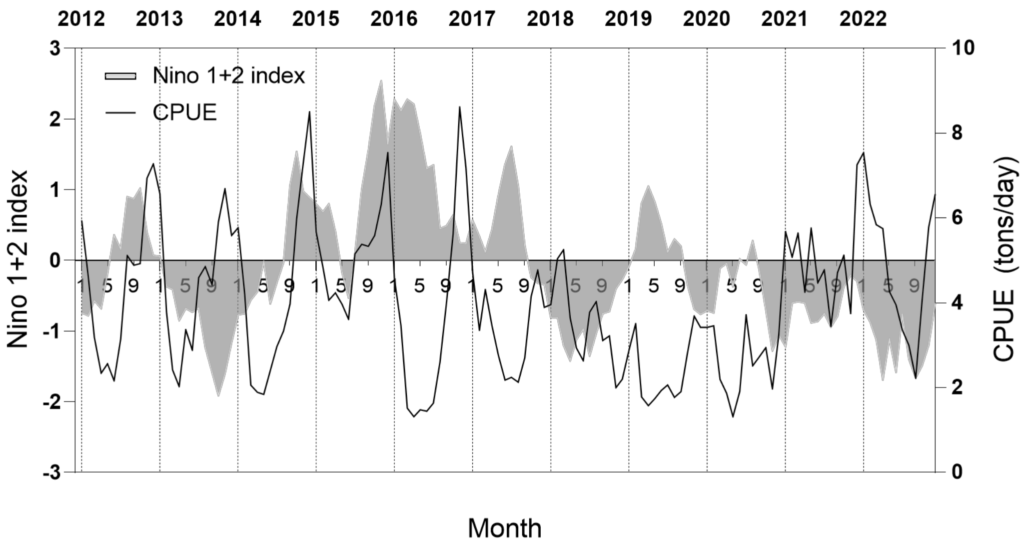


Figure 4 The monthly SSTA of Niño 1+2 area and CPUE from month Jan 2012 to Dec 2022

3.3 Prior distribution

(1) Annual model

Setting appropriate prior distribution is primary in Bayesian paradigm. One base scenario and 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 (Table 2 and 3).

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

Parameter	Basic Scenario	Sensitivity 1
r	uniform (0.1,3)	dlnorm (0.2,0.8)
K	uniform (1200,25000)	uniform (1200,10000)
q_1, q_2, q_3	uniform (0,1)	uniform (0,1)
s	uniform (0.1,3)	uniform (0.5,1.5)
B_{2012}/K	uniform (0.1,1)	uniform (0.1,1)
τ^2	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)

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

Parameter	Basic Scenario	Sensitivity 1
*r*_El_Niño	uniform (0.1,3)	dlnorm (0.2,0.8)
*K*_El_Niño	uniform (1200,25000)	uniform (1200,10000)
*r*_La_Niña	uniform (0.1,3)	dlnorm (0.2,0.8)
*K*_La_Niña	uniform (1200,25000)	uniform (1200,10000)
q_1, q_2, q_3	uniform (0,1)	uniform (0,1)
s	uniform (0.1,3)	uniform (0.5,1.5)
B_{2012}/K	uniform (0.1,1)	uniform (0.1,1)

(2) Monthly model

Adjusting the model to assess in monthly steps, the prior distribution of r needs to be 1/12 of that in the annual model (Table 4 and 5).

Table 4. The prior distributions of parameters for monthly traditional surplus production model

Parameter	Basic Scenario
r	uniform (0,0.25)
K	uniform (1200,25000)
q_1, q_2, q_3	uniform (0,1)
s	uniform (0.1,3)
B_{2012-1}/K	uniform (0.1,1)
τ^2	inverse gamma (0.001,0.001)
σ^2	inverse gamma (0.001,0.001)

Table 5. The prior distributions of parameters for monthly environmental-dependent model

Parameter	Basic Scenario
*r*_El_Niño	uniform (0,0.25)
*K*_El_Niño	uniform (1200,25000)
*r*_La_Niña	uniform (0,0.25)
*K*_La_Niña	uniform (1200,25000)
q_1, q_2, q_3	uniform (0,1)
s	uniform (0.1,3)

B_{2012-1}/K	uniform (0.1,1)
τ^2	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 50,000 times. The first 10,000 times were discarded and the rest values are reserved once every 20 times. The initial value of each chain is shown in Table 6, 7, 8 and 9.

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 6. The initial value of different MCMC chains in annual traditional model

Parameter	K	r	q_1, q_2, q_3	B_{2012}/K	s	τ^2	σ^2
Chain 1	4000	0.5	0.04	0.5	0.5	0.1	0.1
Chain 2	7000	0.7	0.05	0.7	0.7	0.1	0.1
Chain 3	10000	1.0	0.06	1.0	1.0	0.1	0.1

Table 7. The initial value of different MCMC chains in annual environmental dependent model

Parameter	K_El_ Niño	K_La _Niña	r_El_ Niño	r_La_ Niña	$q_{1,2,3}$	B_{2012}/K	s	τ^2	σ^2
Chain 1	4000	4000	0.5	0.5	0.04	0.5	0.5	0.1	0.1
Chain 2	7000	7000	0.7	0.7	0.05	0.7	0.7	0.1	0.1
Chain 3	10000	10000	1.0	1.0	0.06	1.0	1.0	0.1	0.1

Table 8. The initial value of different MCMC chains in monthly traditional model

Parameter	K	r	$q_{1,2,3}$	B_{2012-1}/K	s	τ^2	σ^2
Chain 1	3000	0.06	0.03	0.5	0.8	0.1	0.1
Chain 2	7000	0.11	0.04	0.7	1.1	0.1	0.1
Chain 3	10000	0.15	0.05	1.0	1.5	0.1	0.1

Table 9. The initial value of different MCMC chains in monthly environmental dependent model

Parameter	K_El_ Niño	K_La _Niña	r_El_ Niño	r_La_ Niña	$q_{1,2,3}$	B_{2012-1}/K	s	τ^2	σ^2
Chain 1	3000	3000	0.06	0.06	0.03	0.5	0.8	0.1	0.1
Chain 2	7000	7000	0.11	0.11	0.04	0.7	1.1	0.1	0.1
Chain 3	10000	10000	0.15	0.15	0.05	1.0	1.5	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:

$$B_{MSY} = K(s+1)^{(-1/s)} \quad (5)$$

$$F_{MSY} = r(1 - 1/(s+1)) \quad (6)$$

$$MSY = B_{MSY} \times F_{MSY} \quad (7)$$

$$B_{lim} = 0.3 \times B_{MSY} \text{ (ICES, 2021)} \quad (8)$$

3.6 Projections

For the annual traditional model, F_{2021} as the baseline to set the multi-level fishing mortality coefficient. XF_{2021} and F_{MSY} were used as fishing mortality rates for 2022-2023 to estimate the biomass, annual total allowable catch (TAC), respectively. In this study, X was set as 0.75, 1, 1.25 and 1.5 to do the projections.

For the monthly traditional model, $F_{2021\text{-}12}$ as the baseline to set the multi-level fishing mortality coefficient. $XF_{2021\text{-}12}$ and F_{MSY} were used as monthly fishing mortality rates in 2022 to estimate the biomass, monthly total allowable catch (TAC) for 2022, respectively. X was also set as 0.75, 1, 1.25 and 1.5.

4. Results

4.1 Generalized Additive Model

Four best GAMs based on different time scales and statistical distributions were shown in Table 10. Comparing the results of the cross-validation tests for the GAM models (Table 11), case Gamma Distribution_Year and Gamma Distribution_Month were found to have higher Spearman correlations and lower root mean squared error (RMSE), and thus may be more suitable for CPUE standardization of jumbo flying squid. The annual standardized CPUE and nominal CPUE followed almost identical trend, but differed from the year effect (R^2=0.48, Figure 5). The year effect was used as an abundance index in the stock assessment model. Trends in monthly standardized CPUE, nominal CPUE and monthly effects converged, with the exception of a few months, particularly in August and December 2013 (Figure 6).

Table 10. Best GAM selected based AIC values

Best model in GAM analysis	Distribution	AIC	Explained dev.
ln(CPUE)~Intercept+Year+Month+Region+s(NINO)+s(SSS)+s(SLA)+s(Chl_a)+s(SST)+s(Latitude)+s(Longitude)+s(Latitude:Longitude, by=Month)+ε	Normal	112274.2	22.9%

ln(CPUE)~Intercept+Month+Region+s(SSS)+s(SLA)+s(Chl_a)+s(SST)+s(Latitude)+s(Longitude)+s(Latitude: Longitude, by=Month)+ε	Normal	109268.1	28.3%
CPUE~Intercept+Year+Month+Region+s(NINO)+s(SSS)+s(SLA)+s(Chl_a)+s(SST)+s(Latitude)+s(Longitude)+s(Latitude:Longitude,by=Month)+ε	Gamma	186899.6	22.8%
CPUE~Intercept+Month+s(SSS) +s(SLA)+s(Chl_a)+s(SST)+s(Latitude)+s(Longitude)+s(Latitude: Longitude, by=Month)+ε	Gamma	184006.1	27.7%

Table 11 Five-fold cross validation of the best GAM

Case	Normal Distribution_ Year		Normal Distribution_ Month		Gamma Distribution_ Year		Gamma Distribution_ Month	
	RMSE	Correlation	RMSE	Correlation	RMSE	Correlation	RMSE	Correlation
1	3.94	0.446	3.90	0.502	3.761	0.453	3.74	0.508
2	4.00	0.445	3.97	0.490	3.827	0.450	3.81	0.494
3	3.95	0.448	3.90	0.496	3.743	0.455	3.73	0.505
4	3.99	0.441	3.95	0.488	3.795	0.445	3.78	0.494
5	4.07	0.432	4.04	0.479	3.900	0.438	3.88	0.484

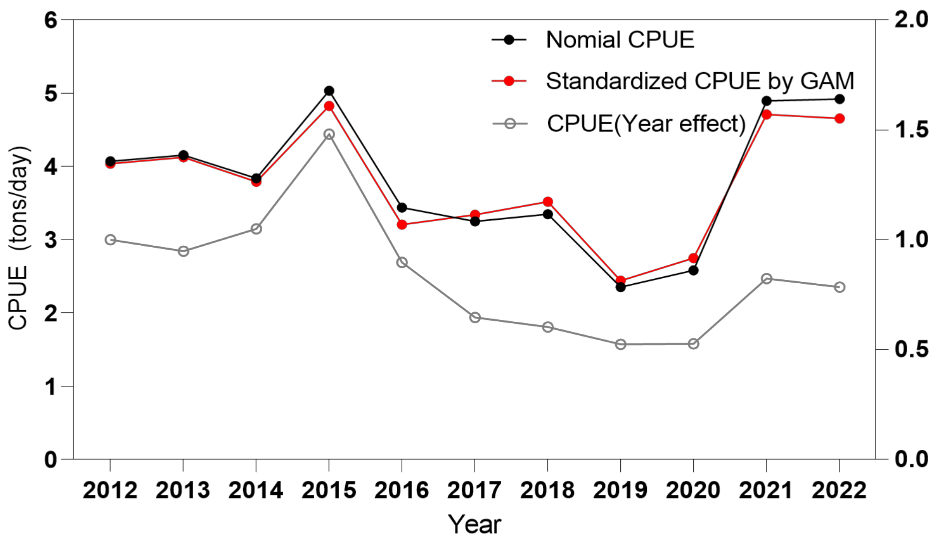


Figure 5. Annual CPUEs for jumbo flying squid (Nominal CPUE on the primary axis, standardized CPUE and year effect on the secondary axis)

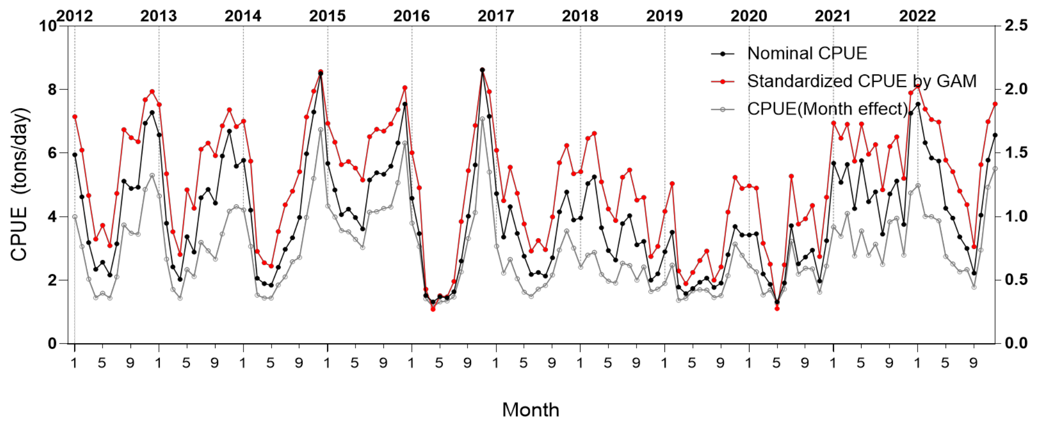


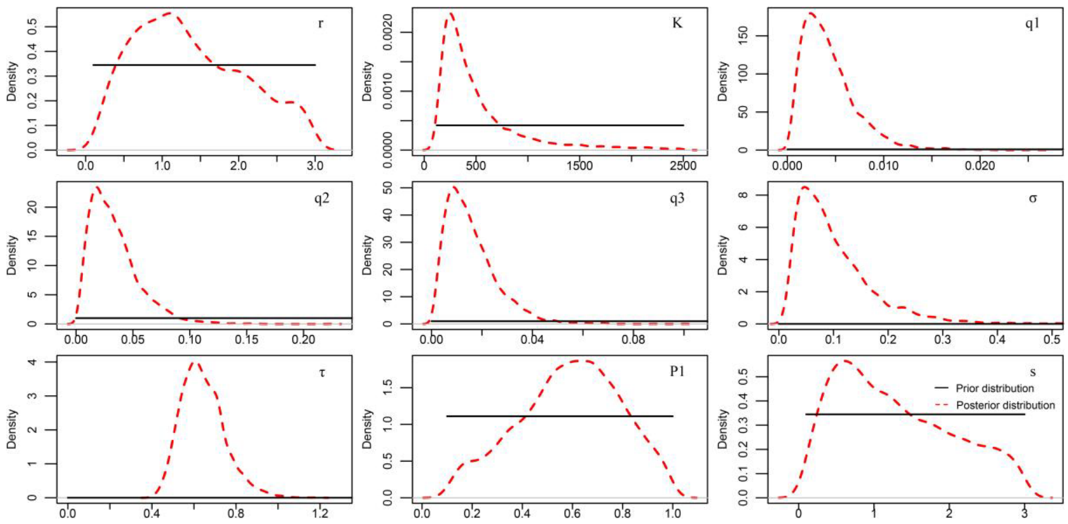
Figure 6. Monthly CPUEs for jumbo flying squid (Nominal CPUE on the primary axis, standardized CPUE and month effect on the secondary axis)

4.2 Estimates of parameters in annual model

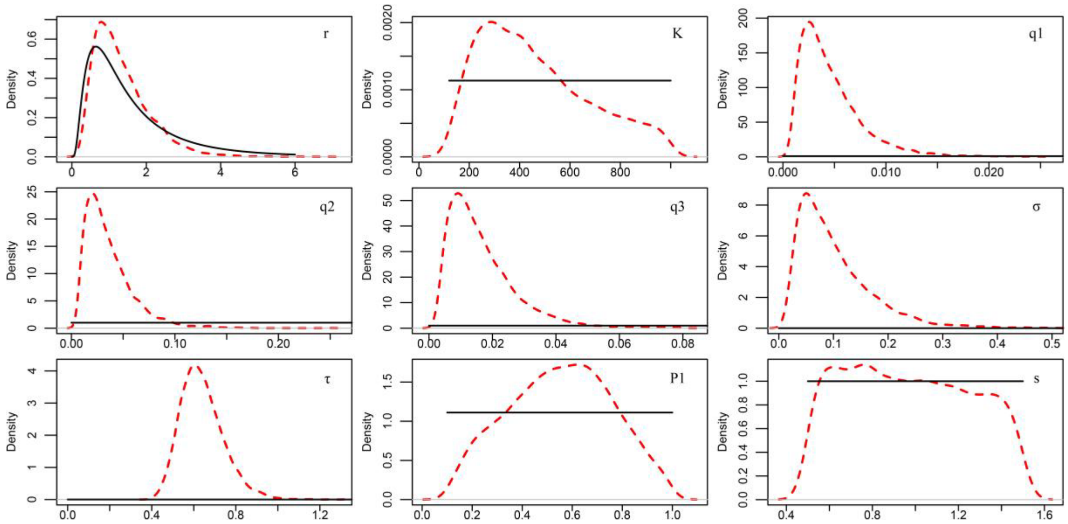
The significant difference between prior distribution and posterior distribution indicated that the data in the model provided sufficient information to dominate the form of posterior distribution in all scenarios (Figure 7 and 8). According to the results of the test, all the model runs in each scenario were converged.

The estimates of parameters for traditional surplus production model were shown in Table 12. For the base scenario, the mean and the median value of parameters r, K, q_1, q_2, q_3, s, σ^2, $\tau^2$and B_{2012}/K were 1.37 and 1.26, 5.18 and 3.74 million tons, 0.004 and 0.004, 0.034 and 0.029, 0.016 and 0.013, 1.28 and 1.15, 0.016 and 0.007, 0.424 and 0.398, 0.59 and 0.60, respectively. For the sensitivity analysis scenario, the mean and the median value of parameters r, K, q_1, q_2, q_3, s and B_{2012}/K were 1.33 and 1.16, 4.60 and 4.17 million tons, 0.005 and 0.004, 0.036 and 0.030, 0.017 and 0.014, 0.97 and 0.96, 0.016 and 0.007, 0.419 and 0.394, 0.55 and 0.56, respectively.

The estimates of parameters for environmental dependent model were shown in Table 13. For the base scenario, the mean and the median value of parameters *r*_El_Niño, *r*_La_Niño, *K*_El_Niño, *K*_La_Niña, q_1, q_2, q_3, s, τ^2, σ^2 and B_{2012}/K were 1.16 and 1.01, 1.47 and 1.40, 9.03 and 7.57 million tons, 8.06 and 6.83 million tons, 0.003 and 0.002, 0.024 and 0.019, 0.011 and 0.009, 0.97 and 0.76, 0.017 and 0.007, 0.421 and 0.393, 0.54 and 0.56, respectively. For the sensitivity analysis scenario, the mean and the median value of parameters *r*_El_Niño, *r*_La_Niño, *K*_El_Niño, *K*_La_Niña, q_1, q_2, q_3, s, τ^2, σ^2 and B_{2012}/K were 1.06 and 0.89, 1.34 and 1.16, 5.80 and 5.72 million tons, 5.21 and 5.09 million tons, 0.003 and 0.003, 0.027 and 0.022, 0.012 and 0.01, 0.96 and 0.94, 0.017 and 0.007, 0.426 and 0.398, 0.57 and 0.59, respectively.



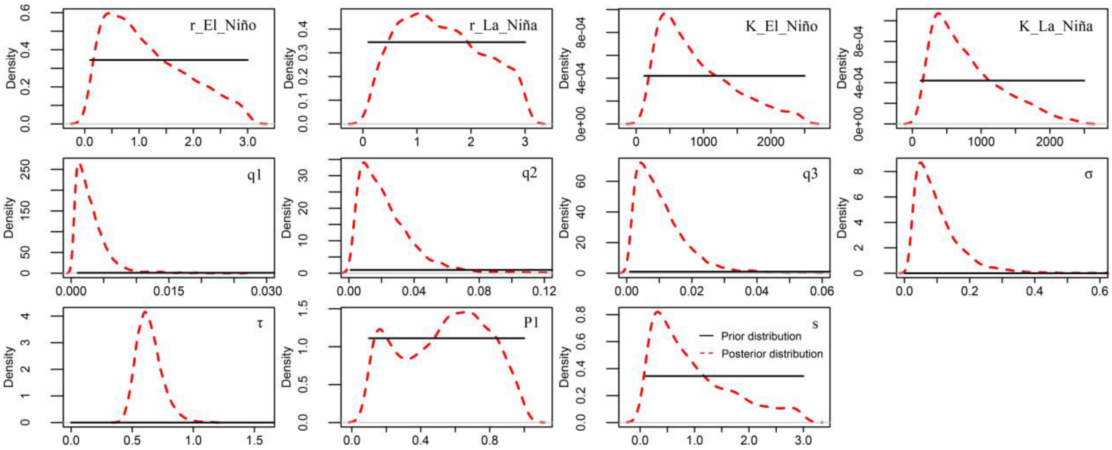
(a)



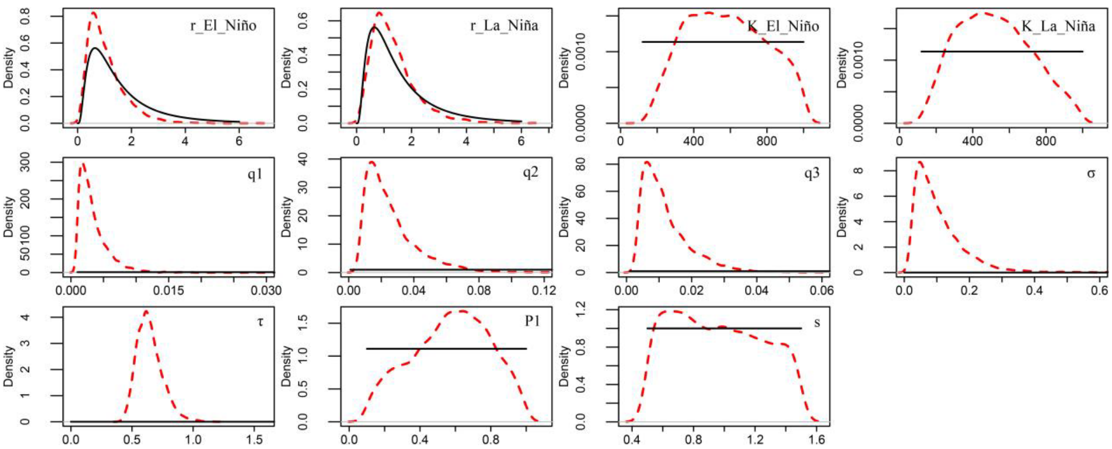
（b）

Figure 7. Prior and posterior distributions of parameters for annual traditional 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, r, q_1, q_2, q_3, σ^2, τ^2, P_1 and s)



(a)



(b)

Figure 8. Prior and posterior distributions of parameters for annual 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, r, q_1, q_2, q_3, σ^2, τ^2, P_1 and s)

Table 12 The estimates of parameters for annual traditional model

Scenario	Statistic	r	K (kt)	q_1	q_2	q_3	s	σ^2	τ^2	B_{2012}/K
Base scenario	mean	1.37	5180.6	0.004	0.034	0.016	1.28	0.016	0.424	0.59
	2.50%	0.27	1484.9	0.001	0.006	0.003	0.18	0.001	0.223	0.17
	25%	0.80	2523.0	0.002	0.018	0.008	0.64	0.003	0.323	0.45
	50%	1.26	3744.5	0.004	0.029	0.013	1.15	0.007	0.398	0.60
	75%	1.91	6152.5	0.006	0.044	0.021	1.85	0.017	0.498	0.74
	97.5%	2.83	18240.2	0.011	0.086	0.040	2.85	0.083	0.779	0.94
Sensitivity scenario	mean	1.33	4604.14	0.005	0.036	0.017	0.97	0.016	0.419	0.55
	2.50%	0.39	1570.85	0.001	0.009	0.004	0.52	0.001	0.222	0.17
	25%	0.78	2868.00	0.002	0.019	0.009	0.72	0.003	0.322	0.40
	50%	1.16	4173.00	0.004	0.030	0.014	0.96	0.007	0.394	0.56
	75%	1.71	6033.25	0.006	0.046	0.022	1.21	0.018	0.489	0.71
	97.5%	3.14	9392.02	0.013	0.096	0.045	1.47	0.079	0.764	0.93

Table 13 The estimates of parameters for annual environmental dependent model

Scenario	Statistic	r_El_Niño	r_La_Niña	K_El_Niño	K_La_Niña	q_1	q_2	q_3	s	σ^2	τ^2	B_{2012}/K
Base	mean	1.16	1.47	9028.58	8059.03	0.003	0.024	0.011	0.97	0.017	0.421	0.54
scenario	2.50%	0.16	0.25	2107.80	1765.95	0.001	0.004	0.002	0.13	0.001	0.220	0.12
	25%	0.55	0.84	4604.00	4035.75	0.001	0.011	0.005	0.39	0.003	0.321	0.33
	50%	1.01	1.40	7571.50	6826.00	0.002	0.019	0.009	0.76	0.007	0.393	0.56
	75%	1.68	2.06	12450.00	11032.50	0.004	0.031	0.014	1.40	0.017	0.489	0.73
	97.5%	2.78	2.90	22461.00	19970.25	0.009	0.070	0.033	2.78	0.093	0.775	0.95
Sensitivity	mean	1.06	1.34	5808.38	5209.19	0.003	0.027	0.012	0.96	0.017	0.426	0.57
scenario	2.50%	0.22	0.28	2172.92	1879.92	0.001	0.008	0.004	0.52	0.001	0.227	0.15
	25%	0.56	0.77	4071.75	3633.00	0.002	0.014	0.007	0.71	0.003	0.324	0.42
	50%	0.89	1.16	5717.00	5090.00	0.003	0.022	0.010	0.94	0.007	0.398	0.59
	75%	1.37	1.71	7484.00	6644.25	0.004	0.033	0.015	1.20	0.019	0.496	0.74
	97.5%	2.80	3.45	9699.10	9193.02	0.009	0.071	0.033	1.46	0.092	0.781	0.95

4.3 Estimates of parameters in monthly model

The results of the prior and posterior distributions were shown in Figures 9 and 10.

The estimates of parameters for traditional surplus production model were shown in Table 14. For the base scenario, the mean and the median value of parameters r, K, q_1, q_2, q_3, s, σ^2, $\tau^2$and $B_{2012\text{-}1}/K$ were 0.18 and 0.20, 4.53 and 3.27 million tons, 0.006 and 0.006, 0.034 and 0.030, 0.004 and 0.003, 1.87 and 1.91, 0.114 and 0.106, 15.7 and 15.6, 0.56 and 0.55, respectively.

The estimates of parameters for environmental dependent model were shown in Table 15. For the base scenario, the mean and the median value of parameters r_El_Niño, r_La_Niño, K_El_Niño, K_La_Niña, q_1, q_2, q_3, s, τ^2, σ^2 and $B_{2012\text{-}1}/K$ were 0.15 and 0.16, 0.16 and 0.17, 8.68 and 6.96 million tons, 5.96 and 4.61 million tons, 0.004 and 0.003, 0.022 and 0.017, 0.002 and 0.002, 1.87 and 1.94, 0.111 and 0.102, 15.6 and 15.5, 0.58 and 0.57, respectively.

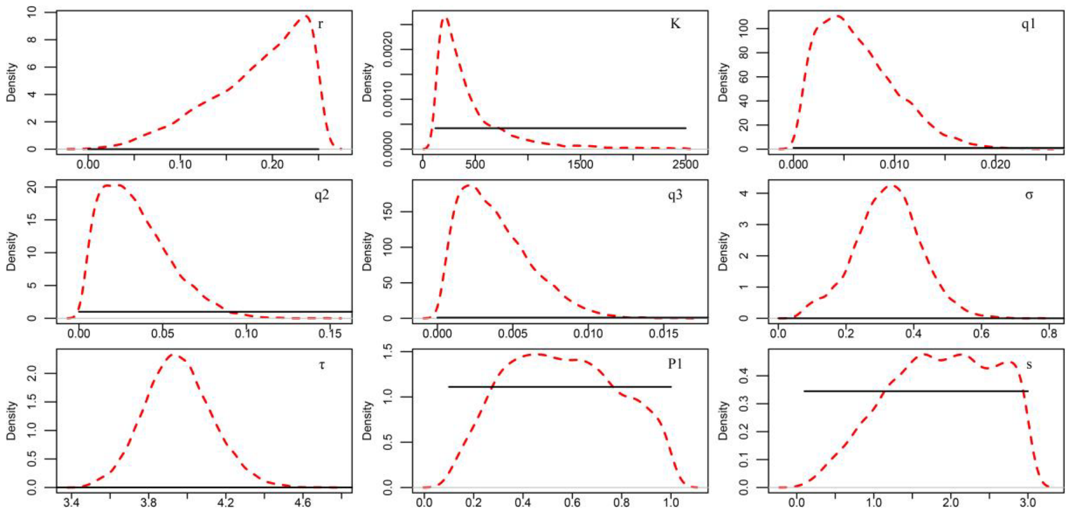


Figure 9. Prior and posterior distributions of parameters for monthly traditional model

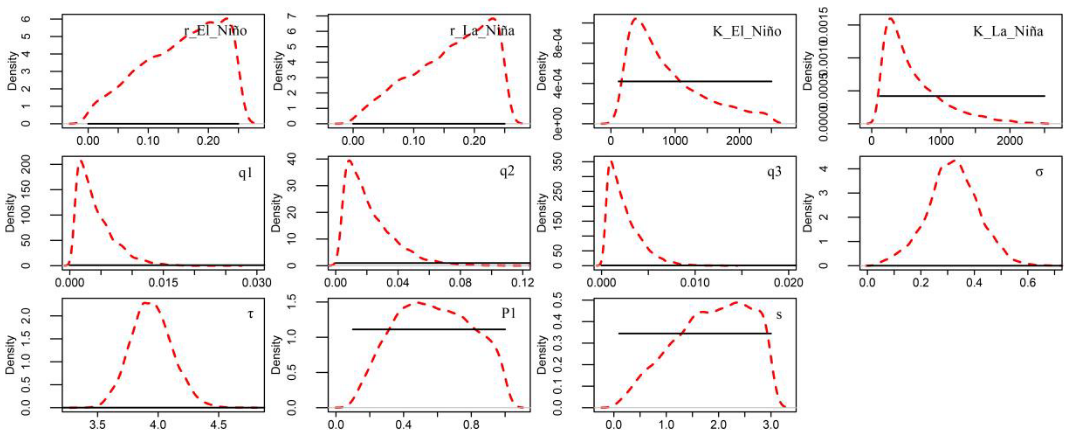


Figure 10. Prior and posterior distributions of parameters for monthly environmental dependent model

Table 14 The estimates of parameters for monthly traditional model

Scenario	Statistic	r	K (kt)	q_1	q_2	q_3	s	σ^2	τ^2	$B_{2012\text{-}1}/K$
Base scenario	mean	0.18	4530.39	0.006	0.034	0.004	1.87	0.114	15.668	0.56
	2.50%	0.06	1343.00	0.001	0.006	0.001	0.51	0.014	13.180	0.17
	25%	0.15	2178.00	0.003	0.018	0.002	1.37	0.068	14.710	0.38
	50%	0.20	3270.00	0.006	0.030	0.003	1.91	0.106	15.590	0.55
	75%	0.23	5349.25	0.009	0.046	0.005	2.45	0.149	16.540	0.73
	97.5%	0.25	15820.00	0.015	0.081	0.009	2.95	0.270	18.650	0.97

Table 15 The estimates of parameters for monthly environmental dependent model

Scenario	Statistic	r_El_Niño	r_La_Niña	K_El_Niño	K_La_Niña	q_1	q_2	q_3	s	σ^2	τ^2	$B_{2012\text{-}1}/K$
Base scenario	mean	0.15	0.16	8680.22	5957.80	0.004	0.022	0.002	1.87	0.111	15.607	0.58
	2.50%	0.02	0.03	2029.87	1428.00	0.001	0.005	0.000	0.42	0.014	13.140	0.18
	25%	0.11	0.12	4214.75	2825.75	0.002	0.010	0.001	1.35	0.067	14.660	0.40
	50%	0.16	0.17	6962.50	4615.00	0.003	0.017	0.002	1.94	0.102	15.530	0.57
	75%	0.21	0.22	11860.00	7971.25	0.006	0.029	0.003	2.46	0.146	16.460	0.75
	97.5%	0.25	0.25	22870.25	17100.50	0.012	0.062	0.007	2.95	0.258	18.450	0.97

4.4 Biological reference points

Three biological reference points were estimated. The results from annual traditional model were shown in Table 16. For the base scenario, the mean and median value of MSY were 1.26 and 1.05 million tons. The mean and median value of B_{MSY} were 2.60 and 1.92 million tons. The mean and median value of F_{MSY} were 0.64 and 0.61. For the sensitivity analysis scenario, the mean and median value of MSY were 1.17 and 1.01 million tons. The mean and median value of B_{MSY} were 2.28 and 2.07 million tons. The mean and median value of F_{MSY} were 0.62 and 0.56.

The results from annual environmental dependent model were shown in Table 17. For the base scenario, the mean and median value of MSY_El_Niño and MSY_La_Niña were 1.56 and 1.16 million tons, 1.83 and 1.43 million tons, respectively. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 4.29 and 3.60 million tons, 3.82 and 3.23 million tons, respectively. The mean and median value of F_{MSY}_El_Niño and F_{MSY}_La_Niña were 0.46 and 0.38, 0.58 and 0.51, respectively. For the sensitivity analysis scenario, the mean and median value of MSY_El_Niño and MSY_La_Niña were 1.23 and 1.05 million tons, 1.41 and 1.25 million tons, respectively. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 2.86 and 2.82 million tons, 2.57 and 2.50 million tons, respectively. The mean and median value of F_{MSY}_El_Niño and F_{MSY}_La_Niña were 0.50 and 0.42, 0.63 and 0.55, respectively.

The results from monthly traditional model were shown in Table 18. For the base scenario, the mean and median value of MSY were 0.29 and 0.20 million tons. The mean and median value of B_{MSY} were 2.54 and 1.82 million tons. The mean and median value of F_{MSY} were 0.115 and 0.119.

The results from monthly environmental dependent model were shown in Table 19. For the base scenario, the mean and median value of MSY_El_Niño and MSY_La_Niña were 0.47 and 0.33 million tons, 0.33 and 0.22 million tons, respectively. The mean and median value of B_{MSY}_El_Niño and B_{MSY}_La_Niña were 4.87 and 3.88 million tons, 3.34 and 2.57 million tons, respectively. The mean and median value of F_{MSY}_El_Niño and F_{MSY}_La_Niña were 0.097 and 0.099, 0.101 and 0.103, respectively.

Table 16 The estimates of biological reference points for annual traditional model

Scenario	Statistic	MSY(kt)	F_{MSY}	B_{MSY}(kt)
Base scenario	mean	1259.25	0.643	2600.89
	2.50%	733.00	0.132	820.16
	25%	901.90	0.392	1311.00
	50%	1050.00	0.614	1915.00
	75%	1375.00	0.859	3043.25
	97.5%	2919.02	1.336	9078.30
Sensitivity	mean	1172.45	0.622	2275.29
	2.50%	730.18	0.198	767.76

scenario	25%	891.70	0.373	1410.00
	50%	1012.00	0.560	2066.00
	75%	1289.00	0.813	2969.25
	97.5%	2565.05	1.369	4681.07

Table 17 The estimates of biological reference points for annual environmental dependent model

Scenario	Statistic	EI_Niño			La_Niña		
		MSY	F_{MSY}	B_{MSY}	MSY	F_{MSY}	B_{MSY}
Base scenario	mean	1561.57	0.456	4286.64	1827.53	0.580	3817.93
	2.50%	378.28	0.066	1132.97	456.78	0.093	941.55
	25%	857.85	0.206	2234.00	1032.50	0.310	1996.75
	50%	1158.00	0.381	3603.00	1428.50	0.511	3230.50
	75%	1780.00	0.653	5800.25	2127.25	0.790	5101.25
	97.5%	5431.20	1.196	10690.00	5615.32	1.375	9516.22
Sensitivity scenario	mean	1231.89	0.493	2861.92	1414.39	0.626	2565.87
	2.50%	398.26	0.105	1085.92	428.44	0.136	943.28
	25%	809.67	0.267	2015.00	957.60	0.368	1804.75
	50%	1045.00	0.419	2819.50	1254.00	0.550	2500.00
	75%	1464.00	0.650	3659.25	1684.25	0.815	3257.00
	97.5%	3102.05	1.247	4834.07	3399.00	1.512	4529.02

Table 18 The estimates of biological reference points for monthly traditional model

Scenario	Statistic	MSY(kt)	F_{MSY}	B_{MSY} (kt)
Base scenario	mean	285.44	0.115	2544.75
	2.50%	68.14	0.036	764.98
	25%	126.57	0.088	1211.00
	50%	195.75	0.119	1819.50
	75%	336.10	0.145	3019.50
	97.5%	1070.30	0.178	8889.15

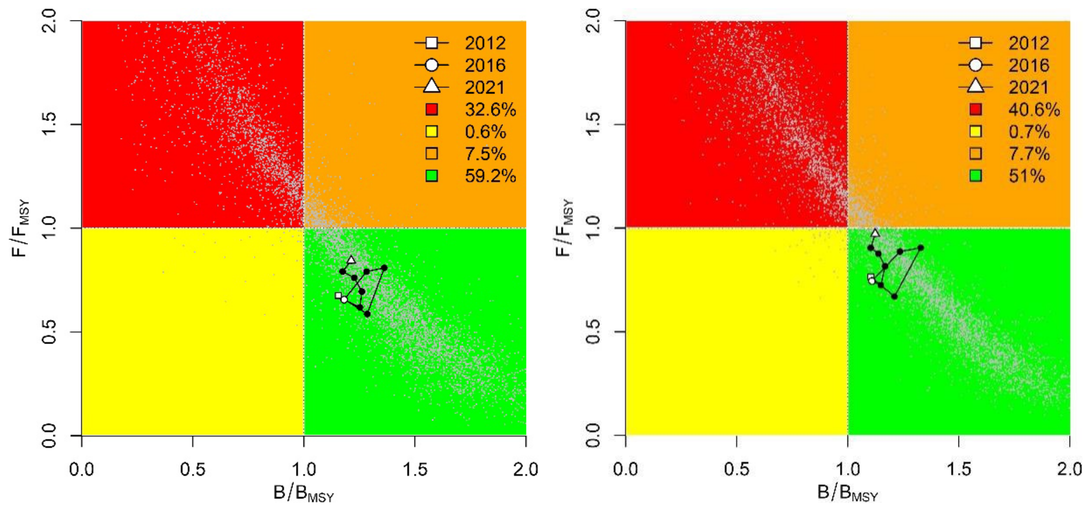
Table 19 The estimates of biological reference points for monthly environmental dependent model

Scenario	Statistic	EI_Niño			La_Niña		
		MSY	F_{MSY}	B_{MSY}	MSY	F_{MSY}	B_{MSY}
Base scenario	mean	467.74	0.097	4867.58	334.29	0.101	3342.85
	2.50%	36.66	0.010	1137.95	41.09	0.015	808.55
	25%	179.17	0.062	2349.00	126.30	0.067	1581.75
	50%	327.30	0.099	3880.50	224.25	0.103	2574.50
	75%	617.90	0.134	6624.25	427.50	0.136	4428.25
	97.5%	1642.10	0.174	13060.00	1240.07	0.175	9766.32

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 of the annual model, 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 59.2% and 51% (Figure 11). The probability of the stock being healthy in the terminal year in environmental dependent model were 59.5% and 61.1% (Figure 12).

The month-based traditional model provided a more detailed reflection of population dynamics. Biomass was greater than B_{lim} in all months, but some months were less than B_{MSY}, i.e., Jan 2011-Feb 2011, Jul 2017-Jan 2018, Jul 2018-Apr 2019, Aug 2020-Dec 2020 and Aug 2021-Dec 2021 (Figure 13a). During these months, the stock is in a state of cautionary. It is necessary to reduce fishing mortality to prevent overfished (Figure 14). Moreover, the fishing mortality for all months were much lower than the F_{MSY} (Figure 13b). The biomass of the monthly environmental dependent model fluctuated even more dramatically (Figure 15). There is a 37.4% probability that the biomass was less than B_{MSY} in the terminal month (Figure 16). The results of the monthly traditional model showed that the biomass in 2018 was less than B_{MSY}, and also in 2021 in the monthly environmental model (Figure 17).



(a) (b)

Figure 11. Kobe plot of annual traditional model, (a) base scenario, (b) sensitivity analysis scenario

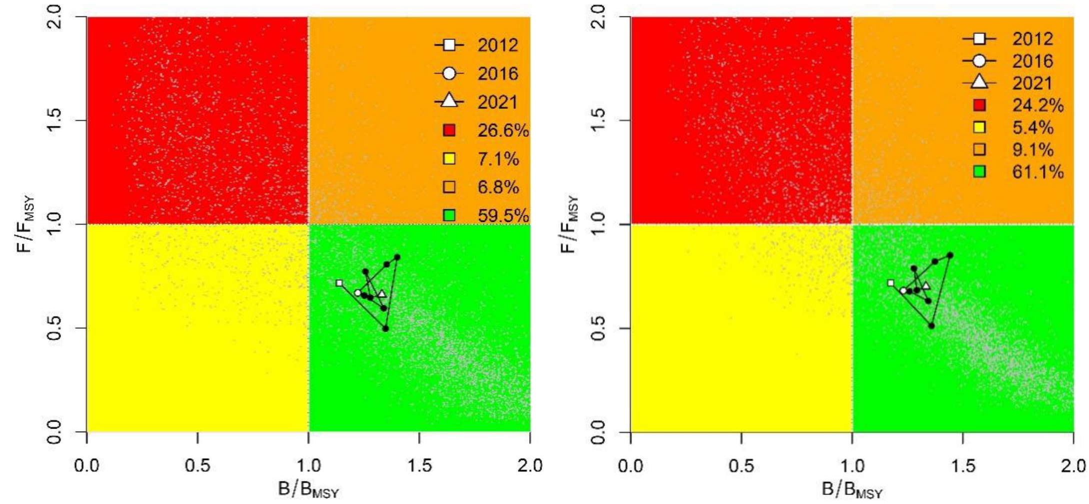
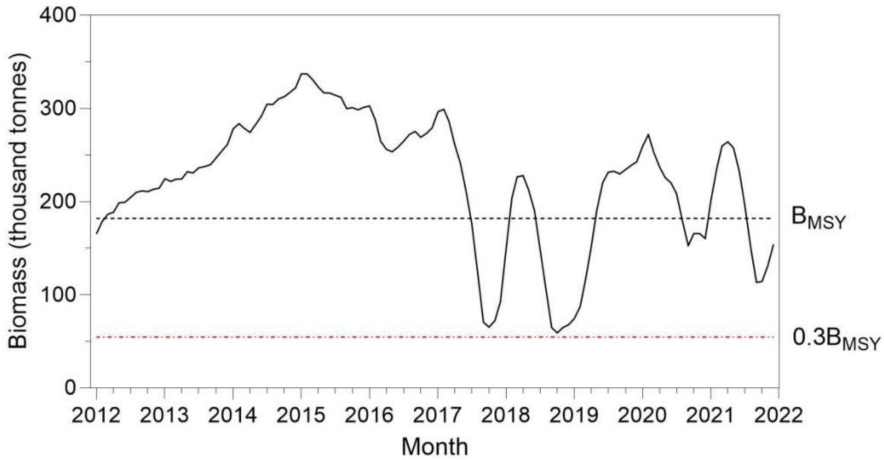
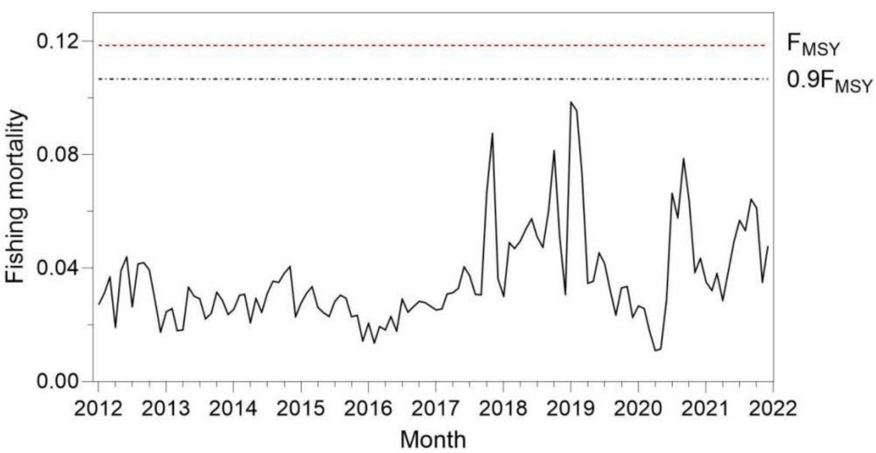


Figure 12. Kobe plot of annual environmental dependent model, base scenario and (b) sensitivity analysis scenario



(a)



(b)

Figure 13. The time series of biomass (a) and fishing mortality (b) for monthly traditional model

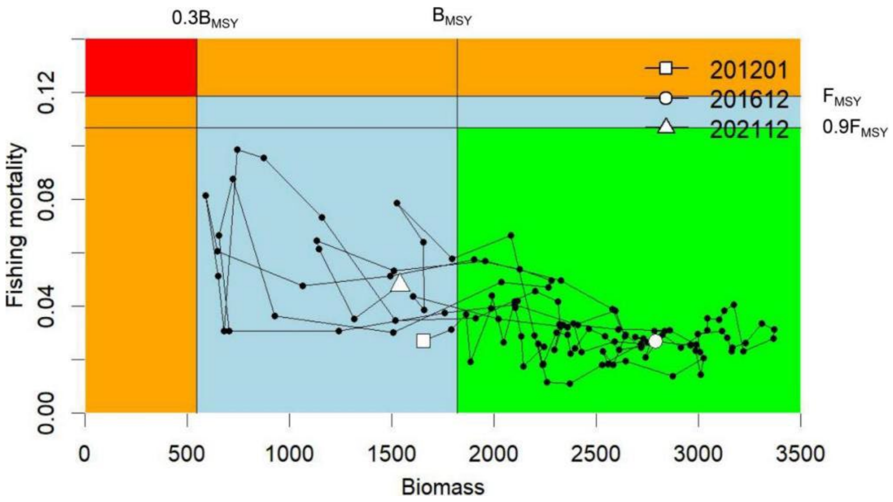
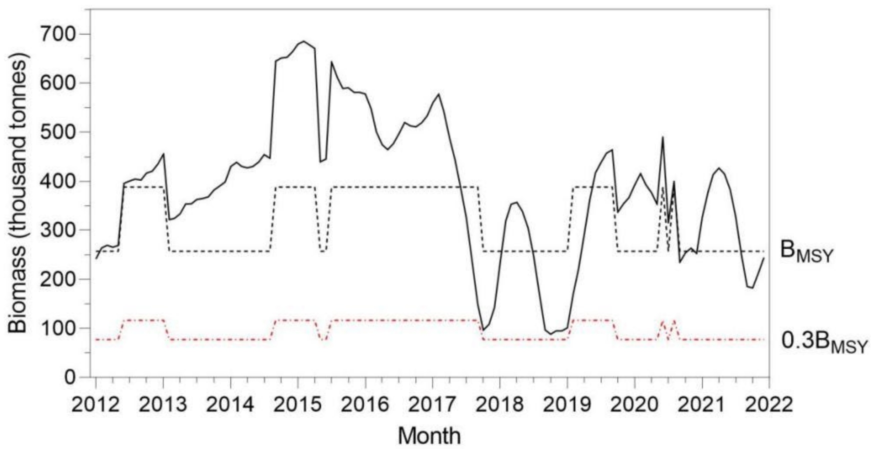
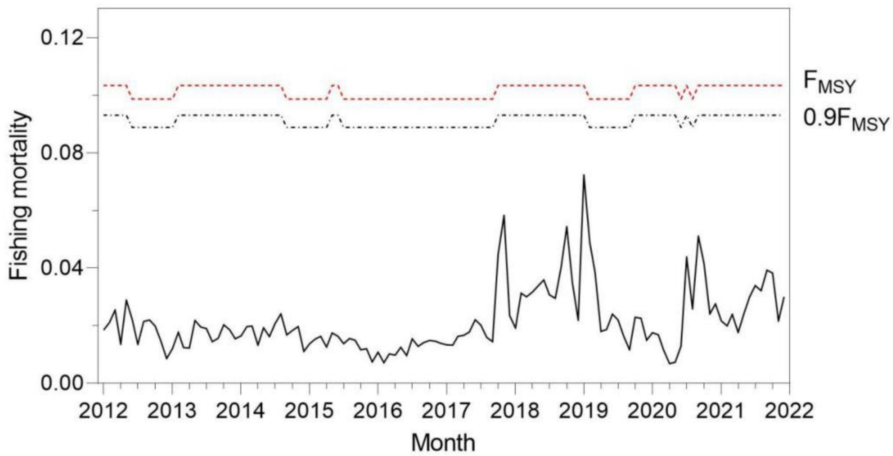


Figure 14. Kobe diagram of monthly traditional model



(a)



(b)

Figure 15. The time series of biomass (a) and fishing mortality (b) for monthly environmental dependent model

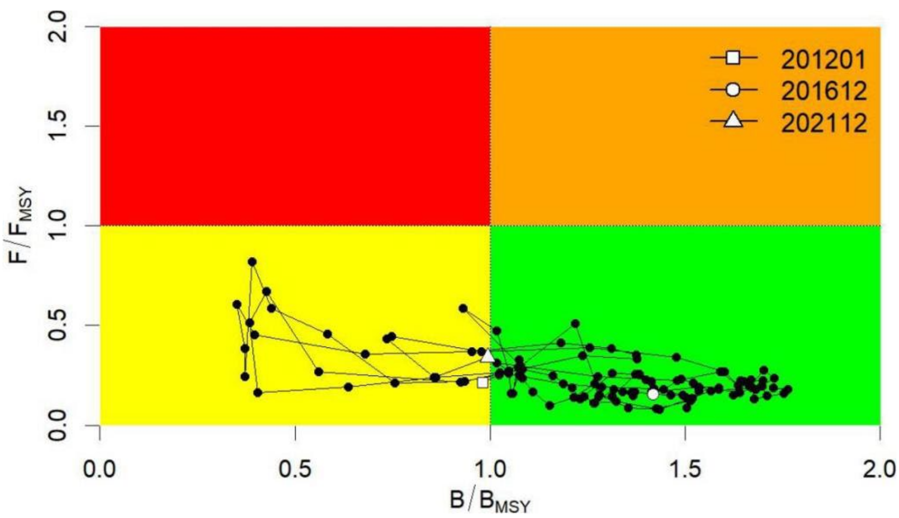


Figure 16. Kobe diagram of monthly environmental dependent model

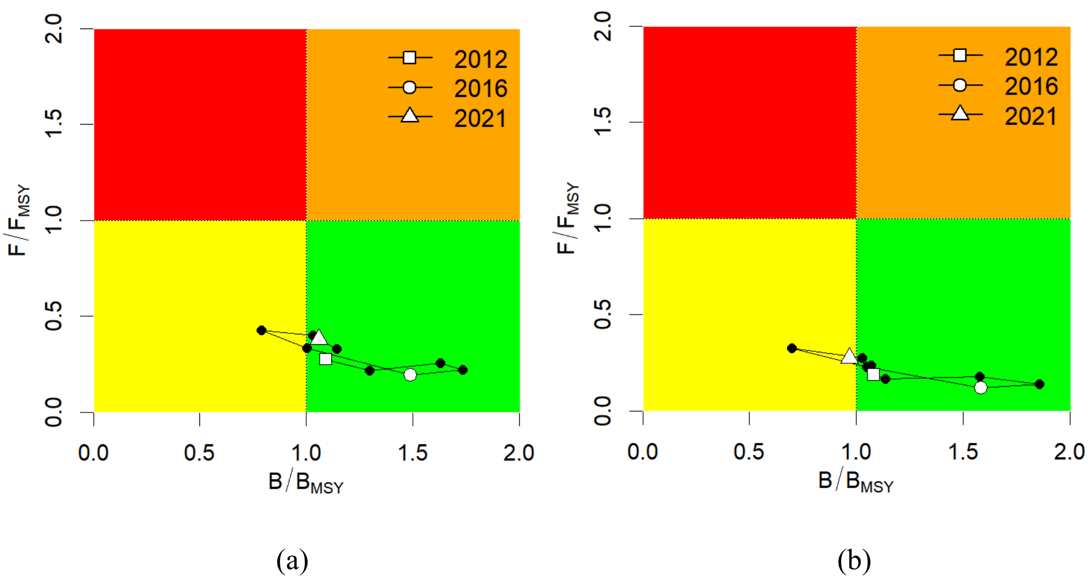


Figure 17. Annual kobe diagram obtained by integrating the monthly model, (a) traditional model, (b) environmental dependent model

4.6 Projections

For a species like jumbo flying squid, which has a short life cycle and is highly susceptible to environmental impacts, it is more reliable to develop a short-term management measure. The status of jumbo flying squid in 2022-2023 was predicted. Biomass would decline when fishing mortality exceeded F_{2021} (Table 20 and 21). Under the fishing mortality rate of F_{2021}, the base and sensitivity scenarios of the traditional model predicted B_{2023}/B_{MSY} of 1.05 and 1.14, TAC of 932 and 929 kt in 2022, 920 and 930 kt in 2023, respectively. Under the fishing mortality rate of $1.25F_{2021}$, the base and sensitivity scenarios of the environment dependent model predicted

B_{2023}/B_{MSY} of 1.11 and 1.03, TAC of 1404 and 1141 kt in 2022, 1133 and 1050 kt in 2023, respectively.

The projection from the monthly model showed an upward trend in biomass that slowed with increasing fishing mortality (Figure 18). Under the fishing mortality rate of $1.5F_{2021\text{-}12}$, the traditional model and environment dependent model predicted the biomass in the last month of 2022 were high at 2034 kt and 3148kt, at which point the TAC would be 144 kt and 141kt, respectively (Table 22 and 23). TAC in 2022 were 1578 kt and 1527kt, respectively.

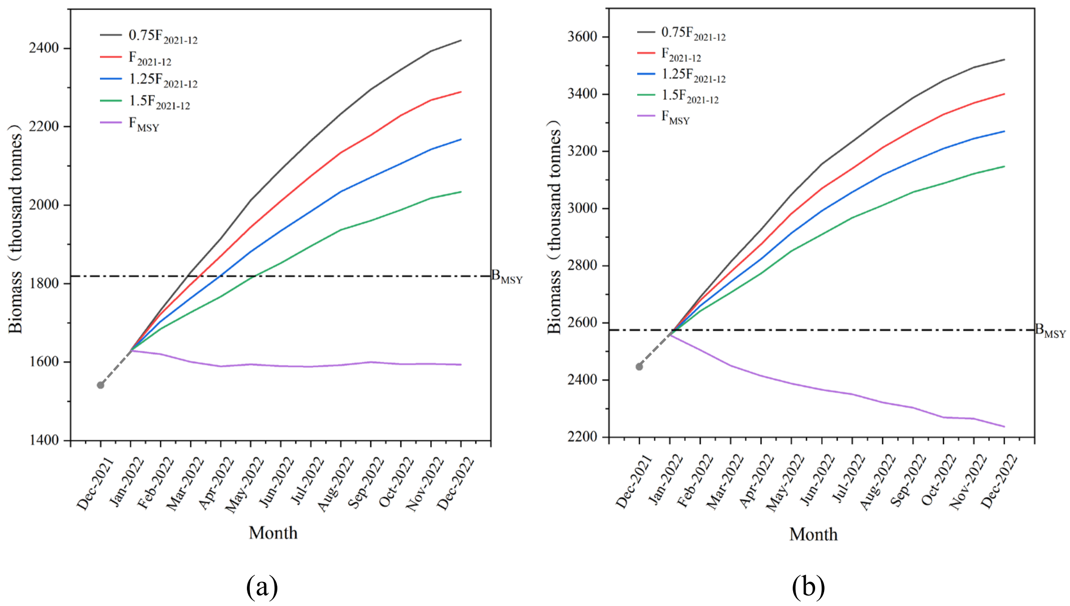


Figure 18. Predicted biomass of jumbo flying squid by monthly traditional model (and environment dependent model (b)

Table 20 Projections for the annual traditional model

Scenarios	Fishing mortality	B_{2023}/B_{MSY}	$P(B_{2023}>B_{2021})$	$P(B_{2023}>B_{MSY})$	B_{2023}	TAC_{2022}	TAC_{2023}
Base	$0.75F_{2021}$(0.500)	1.114	0.44	0.58	2019	754	790
	F_{2021}(0.667)	1.047	0.35	0.54	1898	932	920
	$1.25F_{2021}$(0.834)	0.949	0.27	0.45	1744	1083	990
	$1.5F_{2021}$(1.001)	0.866	0.22	0.34	1617	1211	1020
	F_{MSY}(0.614)	1.113	0.42	0.59	2005	821	860
Sensitivity	$0.75F_{2021}$(0.470)	1.218	0.48	0.69	2118	748	795
	F_{2021}(0.627)	1.140	0.39	0.64	1997	929	930
	$1.25F_{2021}$(0.784)	1.043	0.29	0.55	1845	1083	1002
	$1.5F_{2021}$(0.941)	0.956	0.24	0.45	1715	1215	1046

Table 21 Projections for the annual environment dependent model

Scenarios	Fishing mortality	B_{2023}/B_{MSY}	$P(B_{2023}>B_{2021})$	$P(B_{2023}>B_{MSY})$	B_{2023}	TAC_{2022}	TAC_{2023}
Base	$0.75F_{2021}$(0.274)	1.240	0.57	0.63	3850	918	924
	F_{2021}(0.366)	1.183	0.53	0.61	3698	1172	1133
	$1.25F_{2021}$(0.457)	1.107	0.47	0.57	3464	1404	1271
	$1.5F_{2021}$(0.549)	1.037	0.42	0.52	3252	1616	1373
	F_{MSY}(0.381)	1.168	0.52	0.61	3653	1212	1157
Sensitivity	$0.75F_{2021}$(0.322)	1.157	0.55	0.64	2850	756	785
	F_{2021}(0.430)	1.102	0.44	0.60	2716	959	949
	$1.25F_{2021}$(0.537)	1.025	0.34	0.52	2539	1141	1055
	$1.5F_{2021}$(0.645)	0.954	0.27	0.45	2369	1304	1126

Table 22 Projections for the monthly traditional model

Fishing mortality	$B_{2022\text{-}12}/B_{MSY}$	$P(B_{2022\text{-}12}>B_{2022\text{-}1})$	$P(B_{2022\text{-}12}>B_{MSY})$	$B_{2022\text{-}12}$	$TAC_{2022\text{-}1}$	$TAC_{2022\text{-}12}$	TAC_{2022}
$0.75F_{2021\text{-}12}(0.037)$	1.488	0.86	0.86	2420	59	87	902
$F_{2021\text{-}12}(0.049)$	1.420	0.82	0.84	2289	78	109	1152
$1.25F_{2021\text{-}12}(0.061)$	1.345	0.78	0.80	2168	97	129	1378
$1.5F_{2021\text{-}12}(0.073)$	1.269	0.73	0.75	2034	115	144	1578
$F_{MSY}(0.119)$	0.990	0.54	0.49	1594	182	178	2144

Table 23 Projections for the monthly environment dependent model

Fishing mortality	$B_{2022\text{-}12}/B_{MSY}$	$P(B_{2022\text{-}12}>B_{2022\text{-}1})$	$P(B_{2022\text{-}12}>B_{MSY})$	$B_{2022\text{-}12}$	$TAC_{2022\text{-}1}$	$TAC_{2022\text{-}12}$	TAC_{2022}
$0.75F_{2021\text{-}12}(0.023)$	1.539	0.79	0.88	3521	58	80	850
$F_{2021\text{-}12}(0.031)$	1.502	0.76	0.86	3401	77	102	1073
$1.25F_{2021\text{-}12}(0.038)$	1.458	0.72	0.84	3270	96	122	1307
$1.5F_{2021\text{-}12}(0.046)$	1.411	0.69	0.81	3148	114	141	1527
$F_{MSY}(0.103)$	1.035	0.42	0.53	2238	251	220	2813

References

Arkhipkin, A. I., Hendrickson, L. C., Payá, I., Pierce, G. J., Roa-Ureta, R. H., Robin, J. P., & Winter, A. 2021. Stock assessment and management of cephalopods: advances and challenges for short-lived fishery resources. ICES Journal of Marine Science, 78(2), 714-730.

Hilborn, R., Walters, C.J., 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York, pp. 570.

ICES 2021. Benchmark Workshop on the development of MSY advice for category 3 stocks using Surplus Production Model in Continuous Time; SPiCT (WKMSYSYSPICT). ICES Scientific Reports. Report.

Morales-Bojórquez, E., & Pacheco-Bedoya, J. L. 2016. Jumbo squid Dosidicus gigas: a new fishery in Ecuador. Reviews in Fisheries Science & Aquaculture, 24(1), 98-110.

Nigmatullin, C. M., Nesis, K. N., Arkhipkin, A. I. 2001. A review of the biology of the jumbo squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae). Fisheries Research, 54(1), 9-19.

Taipe, A., Yamashiro, C., Mariategui, L., Rojas, P., & Roque, C. 2001. Distribution and concentrations of jumbo flying squid (Dosidicus gigas) off the Peruvian coast between 1991 and 1999. Fisheries Research, 54(1), 21-32.

Waluda, C. M., Yamashiro, C., and Rodhouse, P. G. 2006. Influence of the ENSO cycle on the light-fishery for Dosidicus gigas in the Peru Current: an analysis of remotely sensed data. Fisheries Research, 79(1-2), 56-63.