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Using a State-space Surplus Production Model to Assess Squid Stock

China

Using a state-space surplus production model to assess the jumbo flying squid (*Dosidicus gigas*) stock in Southeast Pacific (2021)

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Executive summary

In this study, a state-space surplus production model is used to assess the jumbo flying squid stock in Southeast Pacific. The state-space model accounts for process and observation errors. The Bayesian approach is used to estimate parameters and biological reference points.

The population dynamics of jumbo flying squid are highly sensitive to interannual environmental variations. Therefore, the assumption that the key parameters of the model are unique constants is possibly invalid. In this study, an attempt is made to identify two categories for key parameters (i.e., r and K). The categories are determined by sea surface temperature anomaly (SSTA) in the Nino 1+2 area.

The results of the two model scenarios (hereafter traditional model and environmental dependent model) indicate that the biomass of jumbo flying squid in the terminal year is higher than BMSY and the exploitation rate is lower than FMSY.

1. Introduction

Jumbo flying squid, *Dosidicus gigas* (d'Orbigny 1835), is widely distributed in the eastern Pacific Ocean (Nigmatullin et al. 2001). Jumbo flying squid in the Southeast Pacific supports the largest squid fishery in the world. The catch surpassed one million metric ton in 2014 (FAO). The whole fishing ground of jumbo flying squid in this area was approximately located in the area of 0°~30°S, 70°~90°W. Three phenotypical groups of jumbo flying squid in Southeast Pacific has been identified by the distinguishable sizes at which individuals reach maturity (Nigmatullin et al. 2001). In this report, the standardized catch per unit effort (CPUE) data of Chinese vessels were used as biomass abundance indices in a state-space surplus production model developed to describe the dynamics of this stock.

2. Data

2.1 Fishery-dependent data

(1) Catch data

Catch data of jumbo flying squid in the Southeast Pacific Ocean during 2003~2019 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 06/26/2021).

(2) Abundance index data

The abundance index data (CPUE) were from China Distant Water Fisheries Association. The data field consisted of fishing time (month), fishing area (0.25° longitude ×0.25° latitude) and yield. The nominal CPUE is calculated as follows:

$$Nominal\ CPUE_{y,m,i,j} = Catch_{y,m,i,j} / Effort_{y,m,i,j} \quad (1)$$

Where $Catch_{y,m,i,j}$ was the total catch occurred in year y, month m, latitude i and longitude j. $Effort_{y,m,i,j}$ and $Nominal\ CPUE_{y,m,i,j}$ were the total fishing efforts and nominal CPUE, respectively, in the specified spatial grid at the specified time.

The nominal CPUE was standardized by Generalized Linear Model (GLM). The expression of GLM is as follows:

$$ln(Nominal\ CPUE + \sigma) = k + \sum (a_i \times x_i) + \varepsilon \quad (2)$$

The value of σ is 10% of nominal CPUE mean which was added to deal with the 0 value of nominal CPUE. k is the intercept. x_i is an independent variable including environmental factors (i.e. sea surface temperature, concentration of chlorophyll-a) and spatial-temporal factors (i.e. year, month, longitude, latitude). a_i is the related coefficient. ε is the error term which is assumed to follow normal distribution. Environmental data came from remote sensing satellite dataset in National Oceanic and Atmospheric Administration (NOAA) database (http://pifsc-oceanwatch.irc.noaa.gov/erddap/index.html, accessed on 06/28/2021). Sea surface temperature (SST) and concentration of chlorophyll-a (Chl-a) were chosen because these environmental factors were found to greatly affect the jumbo flying squid's habitat and will subsequently influence the fish aggregation and the fishing efficiency (Yu et al. 2016).

The standardized CPUE was used as an abundance index in the surplus production stock assessment model.

3. Stock assessment model

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.

The form of dynamic model is as follows:

$$B_{y+1} = \left(B_y + g\left(B_y\right) - C_y\right)e^{\varepsilon_y} \quad (3)$$

Where B_y is the biomass at the beginning of year y; C_y is catch in year y; I_y is the index of abundance for year y; ε_y is process error which follows normal distribution (e.g. $\varepsilon_y \sim N(0,\sigma_\varepsilon^2)$); $g(B_y)$ is surplus production as a function of B_y and the Schaefer's form is

$$g\left(B_y\right) = rB_y\left(1 - \frac{B_y}{k}\right) \quad (4)$$

Where r is the intrinsic growth rate and k is the capacity denoting the unexploited biomass size.

Pella and Tomlinson considered an extension of Schaefer model:

$$g(B_y) = rB_y(1 - \frac{B_y}{k})^s \quad (5)$$

Equation (4) and (5) are identical when s=1. The reason for the addition of parameter s is that in Schaefer model the surplus production is symmetric in relation to biomass whereas the Pella and Tomlinson's equation allows the relationship to be skewed (Hilborn and Walters 1992).

The form of observation model is as follows:

$$I_y = qB_y e^{\eta_y} \quad (6)$$

Where q is catchability coefficient; η_y is the observation error which follows normal distribution (e.g. η_y~normal(0, σ_η^2)).

State-space model is a kind of model that predicts the future state of a system from its previous states probabilistically (Patterson et al. 2008). Process error and observation error could be simultaneously incorporated into a state-space model. Bayesian approach has been developed to rigorously incorporate expert judgment and inferences into conventional stock assessment and has also been used to convey uncertainties in management strategies to decision maker (McAllister and Kirkwood 1998).

In this study, a 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

The population dynamics of jumbo flying squid are highly sensitive to interannual environmental variations. Therefore, the assumption that the key parameters of the model are unique constants is possibly invalid. In this study, an attempt is made to identify two categories for key parameters (i.e., r and K). The categories are determined by sea surface temperature anomaly (SSTA) in the Nino 1+2 area. Nino 1+2 area ranges from 0 to 10S, and from 90W to 80W, which overlaps with the fishing ground of jumbo flying squid. Parameters r_El_Niño and K_EL_Niño are used to denote r and K for certain years when the SSTA is positive. Parameters r_La_Niña and K_La_Niña are used for the rest of the years when the SSTA is negative (Figure 1).

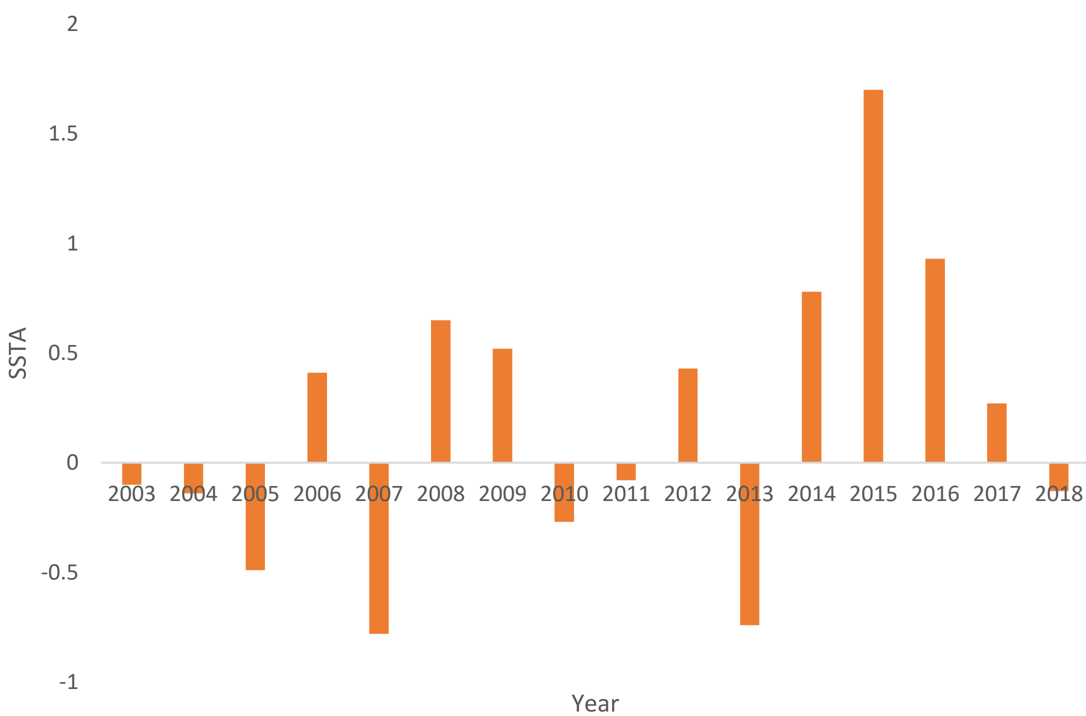

Figure 1 The annual SSTA of Niño 1+2 area from year 2003 to 2018

3.3 Prior distribution

Setting appropriate prior distribution is primary in Bayesian paradigm. In this study, week informative priors are used for parameters. The standard deviations of process and observation error follow gamma distribution and the rest of the parameters follow uniform distribution (Table 1 and 2).

Table 1. The prior distributions of parameters for traditional surplus production model

Parameter	Basic Scenario
r	uniform (0,3)
K	uniform (120,3000)
q	uniform (0,1)
s	uniform (0,3)
B2003/K	uniform (0,1)
σ^2	inverse gamma (0.001,0.001)
τ^2	inverse gamma (0.001,0.001)

Table 2. The prior distributions of parameters for environmental-dependent surplus production model

Parameter	Basic Scenario
r_El_Niño	uniform (0,3)
K_EL_Niño	uniform (120,3000)
r_La_Niña	uniform (0,3)
K_La_Niña	uniform (120,3000)
q	uniform (0,1)
s	uniform (0,3)
B2003/K	uniform (0,1)
σ^2	inverse gamma (0.001,0.001)
τ^2	inverse gamma (0.001,0.001)

3.4 Convergence test

Convergence of the MCMC samples to the posterior distribution was checked by monitoring the trace of four chains of each parameter. Heidelberger and Welch (1983) as well as Gelman and Rubin (1992) diagnostics were also examined.

3.5 Parameters and biological reference points estimation

Monte Carlo Markov Chain (MCMC) is used to estimate model parameters and biological reference points. The estimation process is carried out in Winbugs. Four chains are used and each chain calculates a total of 50,000 times. The first 20,000 times were discarded and the rest values are reserved once every 10 times. The initial value of each chain is shown in Table 3 and 4.

Table 3 The initial value of different MCMC chains in traditional surplus production model

	K	r	q	B2003/K	s	σ^2	τ^2
Chain1	300	0.5	0.05	0.5	0.5	0.1	0.1
Chain2	500	0.6	0.06	0.6	0.6	0.1	0.1
Chain3	700	0.8	0.07	0.8	0.8	0.1	0.1
Chain4	900	1	0.08	1	1	0.1	0.1

Table 4 The initial value of different MCMC chains in environmental-dependent surplus production model

	K_La_Niña	r_La_Niña	K_EL_Niño	r_El_Niño	q	B2003/K	s	σ^2	τ^2
Chain1	300	0.5	300	0.5	0.05	0.5	0.5	0.1	0.1

Chain2	500	0.6	500	0.6	0.06	0.6	0.6	0.1	0.1
Chain3	700	0.8	700	0.8	0.07	0.8	0.8	0.1	0.1
Chain4	900	1	900	1	0.08	1	1	0.1	0.1

4. Results

4.1 Estimates of parameters

The estimates of parameters for traditional surplus production model are shown in Table 5. The mean and median value of carrying capacity K are 6.9 million tons and 4.3 million tons. The mean and median value of intrinsic growth rate r are 1.12 and 1.07. The mean and median value of shape parameter are 0.92 and 0.88. The mean and median value of ratio of B2003/K are 0.76 and 0.78 (Table 5).

The estimates of parameters for environmental-dependent surplus production model are shown in Table 6. The mean and median value of K_EL_Niño are 10.8 million tons and 9.0 million tons. The mean and median value of r_El_Niño are 0.76 and 0.56. The mean and median value of r_La_Niña are 1.33 and 1.27. The mean and median value of shape parameter are 0.87 and 0.88. The mean and median value of ratio of B2003/K are 0.80 and 0.81 (Table 6).

Table 5 The estimates of parameters for traditional model

Parameters	Mean	2.50%	25%	50%	75%	97.50%
K	691.81	202.80	301.10	430.95	814.65	2544.02
r	1.12	0.10	0.63	1.07	1.54	2.51
q	0.02	0.00	0.01	0.02	0.02	0.04
M	0.92	0.52	0.67	0.88	1.15	1.46

σ^2	0.02	0.00	0.01	0.02	0.03	0.06
τ^2	0.07	0.00	0.01	0.05	0.10	0.25
P1	0.76	0.40	0.68	0.78	0.87	0.98

Table 6 The estimates of parameters for environmental dependent model

Parameters	Mean	2.50%	25%	50%	75%	97.50%
r_El_Niño	0.76	0.04	0.27	0.56	1.06	2.56
K_EL_Niño	1078.85	244.30	554.57	900.70	1443.00	2748.00
r_La_Niña	1.33	0.12	0.76	1.27	1.86	2.78
K_La_Niña	1026.58	161.30	308.35	717.15	1619.25	2859.02
q	0.01	0.00	0.00	0.01	0.01	0.03
M	0.87	0.51	0.64	0.82	1.08	1.44
σ^2	0.02	0.00	0.00	0.01	0.03	0.06
τ^2	0.08	0.00	0.02	0.06	0.11	0.27
P1	0.80	0.51	0.71	0.81	0.90	0.99

4.2 Biological reference points

Three biological reference points (i.e., MSY; BMSY; FMSY) are estimated.

The results from traditional model are shown in Table 7. The mean and median value of MSY are 1.2 and 0.97 million tons. The mean and median value of BMSY are 3.4 and 2.1 million tons. The mean and median value of FMSY are 0.50 and 0.51.

The results from environmental dependent model are shown in Table 8. In the years when the SSTA are positive in Nino 1+2 area, the mean and median value of MSY are 1.2 and

0.99 million tons; the mean and median value of BMSY are 3.4 and 2.1 million tons; the mean and median value of FMSY are 0.50 and 0.51.In the years when the SSTA are nagetive in Nino 1+2 area, the mean and median value of MSY are 2.3 and 1.3 million tons; the mean and median value of BMSY are 5.0 and 3.4 million tons; the mean and median value of FMSY are 0.58 and 0.58.

Table 7 The estimates of biological reference points for traditional model

BRP	Mean	2.50%	25%	50%	75%	97.50%
MSY	115.14	46.61	86.31	97.35	116.10	319.33
FMSY	0.50	0.05	0.31	0.51	0.69	1.01
BMSY	339.18	98.94	147.40	210.60	398.55	1256.00

Table 8 The estimates of biological reference points for environmental dependent model

Scenarios	BRP	Mean	2.50%	25%	50%	75%	97.50%
	MSY	121.86	15.30	72.06	98.62	138.30	382.21
EL_Niño	FMSY	0.34	0.02	0.13	0.25	0.46	1.09
	BMSY	523.16	120.00	268.30	435.95	701.67	1329.02
	MSY	234.86	37.47	89.12	131.35	299.70	915.11
La_Niña	FMSY	0.58	0.06	0.36	0.58	0.81	1.13
	BMSY	497.82	79.01	149.77	344.95	785.00	1391.02

4.3 Stock status

The biomass of terminal year is over BMSY, the exploited rate is below FMSY in both traditional model and environmental dependent model (Figure 2 and 3).

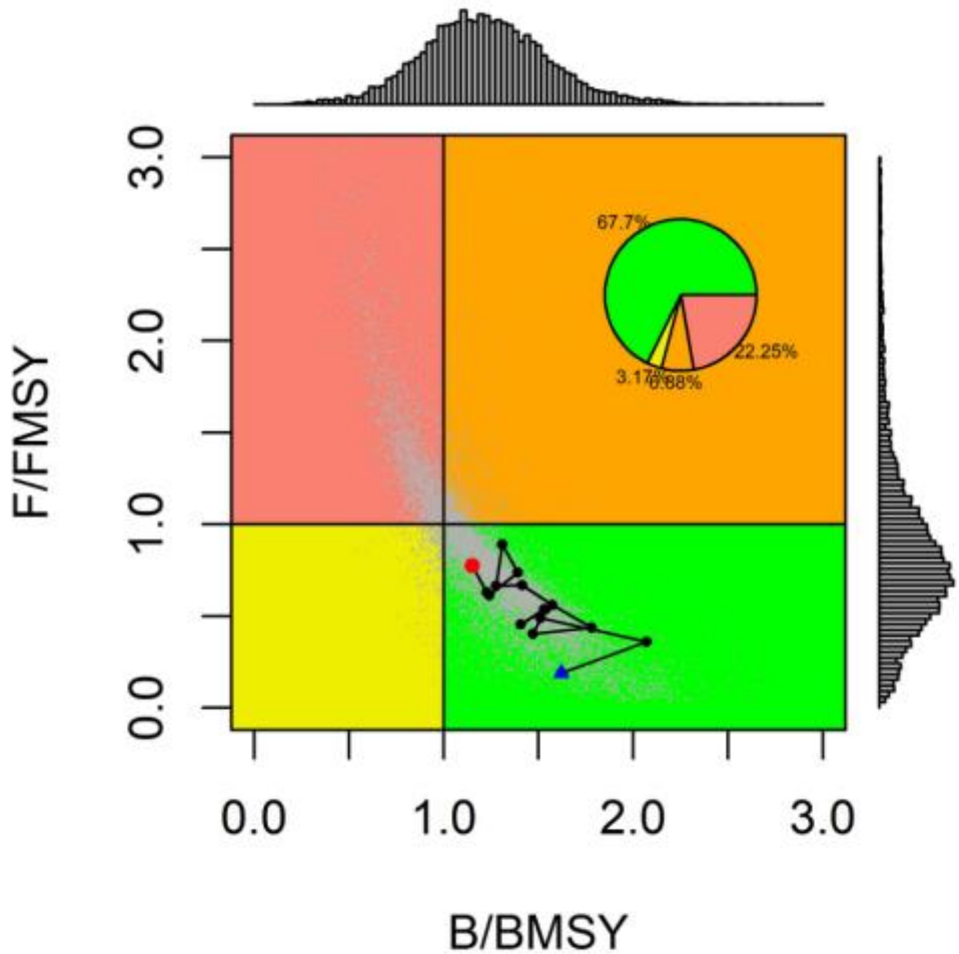

Figure 2 The Kobe plot for traditional model

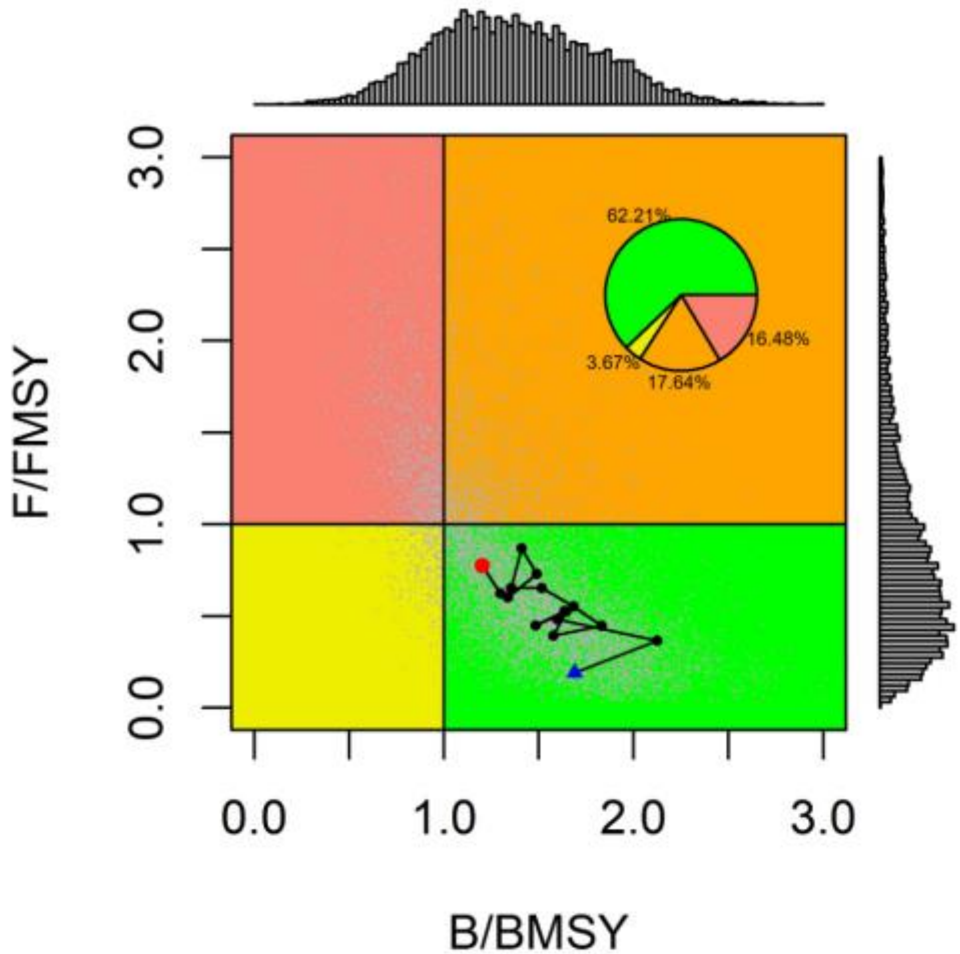

Figure 3 The Kobe plot for environmental dependent model

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