Acta Oceanol. Sin., 2018, Vol. 37, No. 2, P. 94–101
DOI: 10.1007/s13131-017-1131-y
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

A stock assessment for *Illex argentinus* in Southwest Atlantic using an environmentally dependent surplus production model

WANG Jintao[1, 5, 4], CHEN Xinjun[1, 2, 3, 5*], Kevin W. Staples[4], CHEN Yong[4, 1]

[1] College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China

[2] National Distant-water Fisheries Engineering Research Center, Shanghai Ocean University, Shanghai 201306, China

[3] Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources of Ministry of Education, Shanghai Ocean University, Shanghai 201306, China

[4] School of Marine Sciences, University of Maine, Orono, Maine 04469, USA

[5] Collaborative Innovation Center for National Distant-water Fisheries, Shanghai 201306, China

Received 25 June 2016; accepted 14 February 2017

Abstract

The southern Patagonian stock (SPS) of Argentinian shortfin squid, *Illex argentinus*, is an economically important squid fishery in the Southwest Atlantic. Environmental conditions in the region play an important role in regulating the population dynamics of the *I. argentinus* population. This study develops an environmentally dependent surplus production (EDSP) model to evaluate the stock abundance of *I. argentines* during the period of 2000 to 2010. The environmental factors (favorable spawning habitat areas with sea surface temperature of 16–18°C) were assumed to be closely associated with carrying capacity (K) in the EDSP model. Deviance Information Criterion (DIC) values suggest that the estimated EDSP model with environmental factors fits the data better than a Schaefer surplus model without environmental factors under uniform and normal scenarios. The EDSP model estimated a maximum sustainable yield (MSY) from 351 600 t to 685 100 t and a biomass from 1 322 400 t to 1 803 000 t. The fishing mortality coefficient of *I. argentinus* from 2000 to 2010 was smaller than the values of $F_{0.1}$ and F_{MSY}. Furthermore, the time series biomass plot of *I. argentinus* from 2000 to 2010 shows that the biomass of *I. argentinus* and this fishery were in a good state and not presently experiencing overfishing. This study suggests that the environmental conditions of the habitat should be considered within squid stock assessment and management.

Key words: *Illex argentinus*, stock assessment, Schaefer surplus production model, environmental factors, Southwest Atlantic

Citation: Wang Jintao, Chen Xinjun, Kevin W. Staples, Chen Yong. 2018. A stock assessment for ***Illex argentinus*** in Southwest Atlantic using an environmentally dependent surplus production model. Acta Oceanologica Sinica, 37(2): 94–101, doi: 10.1007/s13131-017-1131-y

1 Introduction

The Argentinian shortfin squid, *Illex argentinus*, is one of the most economically important species in the Southwest Atlantic. It is widely distributed across the Patagonian Shelf and in adjacent oceanic waters, occurring between 22°S and 54°S (Haimovici et al., 1998). In 1997, Chinese fleets started to exploit *I. argentinus* in the waters bounded by 43°–50°S and 55°–61°W (Lu et al., 2013a). The annual catch of this squid exploited by Chinese squid-jigging vessels ranged from 5 215 t to 99 387 t during 2000 to 2010.

The population structure of *I. argentinus* is complex and can be divided into three or four stocks based on length at maturity, area, time of spawning, the distribution of early life stages, juveniles and adults (Brunetti et al., 1998; Haimovici et al., 1998). The most abundant winter-hatched population of squid, known as the southern patagonic stock (SPS), is targeted by Chinese squid-jigging fleets (Lu et al., 2013a). The SPS undertakes long-distance migrations between the winter hatching grounds in the region of the northern Patagonian shelf/slope and the summer feeding grounds in the south (Hatanaka, 1998; Haimovici et al., 1998; Arkhipkin, 2000).

Extensive research has been conducted to study the fishery biology, abundance and fishing ground distribution of *I. argentinus* in recent decades (Arkhipkin, 1993; Arkhipkin and Laptikhovsky, 1994; Haimovici et al., 2014; Rosas-Luis et al., 2014; Waluda et al., 2001, 2008). This research has indicated that squid abundance is significantly affected by the environmental conditions at the spawning grounds. For example, Waluda et al. (2001) found that high squid abundance was associated with a higher proportion of favorable-SST waters within the inferred hatching area in the year preceding recruitment to the fishery.

The Leslie-Delury model (Basson et al., 1996) has rarely been

---

Foundation item: The National Natural Science Foundation of China under contract No. NSFC31702343; the Science Foundation of Shanghai under contract No. 13ZR1419700; the Innovation Program of Shanghai Municipal Education Commission under contract No. 13YZ091; the National High-tech R&D Program of China (863 Program) under contract No. 2012AA092303; the Funding Program for Outstanding Dissertations in Shanghai Ocean University; the Funding Scheme for Training Young Teachers in Shanghai Colleges and the Shanghai Leading Academic Discipline Project (Fisheries Discipline); Involvement of Chen Yong was supported by SHOU International Center for Marine Studies and Shanghai 1000 Talent Program.

*Corresponding author, E-mail: xjchen@shou.edu.cn

used to analyze catch data of *I. argentinus* to determine the annual stock size. Traditional age- or length-structured models have had difficulty evaluating the influence of intensive commercial jigging fleets on *I. argentinus* stock size due to its unique life history. The methods for assessing short-lived species, such as ommatrephid squids, have greatly improved in recent years. Ichii et al. (2006) evaluated the annual biomass of fall cohorts for 1982–1992 on the driftnet fishing grounds using the ASPIC none equilibrium biomass dynamic model (Prager, 1994) and the DeLury depletion model (Hilborn et al., 1993). For the winter-spring cohort of *Ommastrephes bartramii*, Chen et al. (2008) fit a modified depletion model to the Chinese squid-jigging fisheries data to estimate the squid stock abundance from 2000 to 2005. The annual maximum allowable catch ranged from 80 000 t to 100 000 t and was consistent with estimations by Osako and Murata (1983) for the annual sustainable catch of the western stock. However, as short-lived ecological opportunists, *I. argentinus* are typically subject to large fluctuations in abundance, responding rapidly to changes in environmental conditions (Waluda et al., 2008). Therefore, environmental variables are considered to be indispensable factors in assessments of *I. argentinus* stocks.

The environmentally dependent surplus production (EDSP) model evolved from the traditional surplus production model. In surplus production models, fish population dynamics and fishing processes that include natural mortality, growth, recruitment, and fishing mortality are assumed to be a function of a single aggregated measure of biomass (Wang et al., 2014). This approach may be applicable for species with short life cycles and limited availability of age/size composition data (Zhan, 1995). Research also has shown that surplus production models can provide more accurate and precise estimates of management-related quantities than complex models (Wang et al., 2014). *Illex argentinus* is a short-lived species and highly susceptible to variations in environmental conditions, therefore, the EDSP model tends to be a better method to assess its stock.

In this study, the influence of the environmental factors on the abundance of SPS cohort of *I. argentinus* are evaluated by analyzing the correlation between the areas occupied by favorable SST on the spawning ground and CPUE. Furthermore, an optimal EDSP model is selected to estimate the stock abundance and reference points, using more informed K and r values for better fishery management.

2 Materials and methods

2.1 *Fishery data*

Data on daily catch (t), effort (days fished), fishing dates and locations (longitude and latitude) were obtained from the Chinese commercial jigging fleets operating in the areas between 43°–50°S and 55°–61°W in the Southwest Atlantic Ocean from January to May during 2000 to 2010. One unit of fishing area was defined as 0.5° latitude by 0.5° longitude.

Chinese jigging vessels had almost identical fishing power and operation, therefore, catch per unit of effort (CPUE) of the squid-jigging vessels was a reliable indicator of stock abundance on the fishing ground (Lu et al., 2013b). The monthly nominal CPUE in one fishing unit of 0.5°×0.5° was calculated as follows:

$$CPUE_{ymi}=\frac{C_{ymi}}{F_{ymi}}, \tag{1}$$

where $CPUE_{ymi}$ is monthly CPUE (t/d) at i fishing unit in month m and year y, C_{ymi} is monthly catch (t) at i fishing unit in month m and year y, and F_{ymi} is number of fishing vessels at i fishing unit in month m and year y.

After 2000, the SPS cohort of *I. argentinus* was mainly caught by Chinese mainland (Lu et al., 2013b), Taiwan Province of China (Chen and Chiu, 2009) and Falkland Islands (Waluda et al., 1999). So we collected total annual catch of SPS caught by those countries to assess SPS cohort of *I. argentinus* in the Southwest Atlantic Ocean during 2000 to 2010. The annual catches of SPS cohort out the exclusive economic zones were obtained from Squid Fishing Technology Group of Shanghai Ocean University and official website of Taiwan of China. Catches of SPS cohort in the exclusive economic zones were sourced from the website of the Falkland Islands Government Administration (Table 1).

Table 1. Catch for the SPS cohort of *I. argentinus* in the Southwest Atlantic Ocean during 2000 to 2011

Year	Catch/t			
	Chinese mainland	Taiwan of China	Falkland Islands	Total catch
2000	75 159	131 278	206 250	412 687
2001	55 778	141 679	150 631	348 088
2002	77 239	95 073	13 411	185 723
2003	96 281	123 668	103 375	323 324
2004	13 265	9 775	1 720	24 760
2005	40 488	35 725	7 937	84 150
2006	79 757	125 929	85 614	291 300
2007	99 387	284 707	161 402	545 496
2008	86 166	208 641	106 600	401 407
2009	15 552	56 092	31 457	103 101
2010	5 215	30 543	66 547	102 305

2.2 *Satellite remote sensing data*

Monthly SST, SSH and Chl *a* concentration data during 2000–2010 in the regions between 30°–55°S and 40°–70°W were obtained from the Live Access Server of National Oceanic and Atmospheric Administration OceanWatch (http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset). The spatial resolution of SST, SSH and Chl *a* concentration data were 0.1°×0.1°, 0.25°×0.25°, and 0.05°×0.05°, respectively. All the environmental data were then converted to 0.5°×0.5° grid for each month in order to correspond to the spatial grid of CPUE (Wang et al., 2016).

2.3 *Standardizing yearly CPUE by generalized linear Bayesian model*

CPUE was commonly assumed to be proportional to stock abundance, therefore, it was usually considered as a relative abundance index in monitoring and assessment of a fish stock (Maunder and Punt, 2004). Lu et al. (2013b) suggested that the generalized linear Bayesian model (GLBM) was a better model to standardize yearly CPUEs for Chinese mainland which represented the same proportional change in stock size of *I. argentinus*. The CPUE was assumed to be normally distributed and log-transformed with errors in the GLBM modeling. The relationships between CPUE and environmental variables were likely to be non-linear (Bigelow et al., 1999). The GLBM for the CPUE standardization in this study can be written as

$$\begin{aligned}\mathrm{Ln}(CPUE+c)=&\,factor(year)+factor(month)+s(longitude)\\&+s(latitude)+s(SST)+s(SSH)+s(Chl\ a)+\varepsilon,\end{aligned} \tag{2}$$

where s is a spline smoother function, constant c was assumed to be 10% of mean CPUE, var $\varepsilon=\sigma^2$ and $E(\varepsilon)=0$.

2.4 *Environmentally dependent surplus production models*

Previous studies indicated that the area occupied by favorable SST (16–18°C) on the inferred hatching ground (32°–39°S, 49°–61°W, P_s) during hatching season (June–August) determined the recruitment of *I. argentinus* in the next year. Therefore, P_s could be used to characterize the suitable of hatching habitat (Waluda et al., 2001). In this study, we used Schaefer's surplus production models to assess *I. argentinus* stock combined with environmental factors.

Schaefer's surplus production model was expressed as

$$B_t = B_{t-1} + rB_{t-1}\left(1-\frac{B_{t-1}}{K}\right) - C_{t-1}, \tag{3}$$

$$I_t = qB_t \mathrm{e}^{\varepsilon_t - \frac{\sigma^2}{2}}, \tag{4}$$

We hypothesized that carrying capacity changed in proportion to P_s for *I. argentinus*. Therefore, environmentally dependent surplus production (EDSP) model with parameter of P_s was given by

$$B_t = B_{t-1} + rB_{t-1}\left(1-\frac{B_{t-1}}{P_s K}\right) - C_{t-1}, \tag{5}$$

where B_t was biomass in t year, K was carrying capacity, C_{t-1} was annual catch in t–1 year, r was intrinsic rate of growth, q was catch ability coefficient, and I_t was CPUE in t year. We assumed the relationship between I_t and B_t was proportional, ε_t was error term, σ was standard deviation. Usually, we consider the fishery resources equals K in the initial year of fishery for reduce the number of parameters (Hilborn and Walters, 1999). Based on Basson's et al. (1996) study, we assumed that the initial biomass of *I. argentinus* was B_0, and the biomass in 2000, was 25×10^5 t. Likelihood function and prior distribution of parameters in Bayesian inference were sated as follows:

(1) Likelihood function

We fitted Schaefer's surplus production models by Bayesian inference. Likelihood function was used to estimate the degree of fitting between the observation data and data predicted by surplus production models (Li et al., 2011). We assumed observation errors followed the log-normal distribution, and the likelihood function was written as

$$L(I|\theta)=\prod_{2000}^{2010}\frac{1}{I_t\sigma\sqrt{2\pi}}\exp\left\{\frac{\left[\log(I_t)-\log(qB_t)\right]^2}{2\sigma^2}\right\}, \tag{6}$$

Due to the short time series of catch and CPUE data (only included 11 years), it tended to be difficult in estimating σ. We assumed σ was 0.2 (McAllister and Kirkwood, 1998).

(2) Setting prior distribution of models parameters

The parameters r, K and q were considered to be uniform and normal distribution, and prior distribution for the parameters r, K and q were listed in Table 2.

(3) Calculating posterior distribution of parameters

The posterior distribution of parameters of Schaefer models were calculated by the method of Markov Chain Monte Carlo (MCMC). The initial values for the parameters of models in MCMC iterations were set as follows: Intrinsic rate of growth was 1, carrying capacity was 1 500 000 t, and the catchability coefficient was 0.2×10^{-5}. The number of MCMC iterations was 50 000, the first 10 000 results of iterations were discarded. For the later 40 000 times, we saved the results for every 40 times.

The fishery management reference points including F_{MSY} (fishing mortality corresponding to MSY), B_{MSY} (annual biomass corresponding to MSY), $F_{0.1}$ and MSY (Table 3) were estimated. The model with the lowest Deviance Information Criterion (DIC) was selected to be the best model.

3 Results

3.1 *Compare the nominal CPUE with the GLBM-standardized CPUE*

The GLBM model was constructed based on the temporal (year and month), spatial (latitude and longitude) and environmental (SST, SSH and CHL) factors. The annual nominal CPUE was compared with the GLBM-estimated standardized CPUE during 2000 to 2010 (Fig. 1). There was a big difference between nominal CPUE and GLBM-standardized CPUE. The nominal CPUE subjected to strong fluctuations comparing with relatively weak variability in the GLBM-standardized CPUE. The annual GLBM-standardized CPUE was basically less than the nominal CPUE. The highest nominal CPUE was 25.3 t/d in 2008, while the highest GLBM-standardized CPUE occurred in 2009 with the value of 8.8 t/d.

3.2 *P_s and abundance index*

Correlations between the abundance index of *I. argentinus* and the monthly P_s in June, July and August showed that the abundance was significantly correlated with P_s in the July (Tables 4 and 5, Fig. 2).

3.3 *Comparison of surplus production models*

The results of two surplus production models under the different scenarios indicated that the biomass and the fishery of *I. argentinus* were in good state at present, and the resource of this species was at a high level without overfishing (Tables 6 and 7, Fig. 3).

Table 2. Scenarios for different settings of prior distribution for the parameters r, K and q of surplus production models

Scenario	Intrinsic rate of growth (r)	Carrying capacity (K)	Catchability coefficient (q)
Uniform distribution	U(0.5, 1.5)	U(70, 400)	U(1×10^{-6}, 8×10^{-5})
Normal distribution	N(1, 0.6^2)	N(350, 35^2)	N[1×10^{-6}, $(5\times10^{-5})^2$]

Table 3. The fishery management reference points for *I. argentinus* in the Southwest Atlantic

Management reference point	Catch	Fishing mortality coefficient	Biomass
SP model	$MSY=rK/4$	$F_{\mathrm{MSY}}=r/2$, $F_{0.1}=0.45r$	$B_{\mathrm{MSY}}=K/2$
EDSP model	$MSY=rP_sK/4$	$F_{\mathrm{MSY}}=r/2$, $F_{0.1}=0.45r$	$B_{\mathrm{MSY}}=P_sK/2$

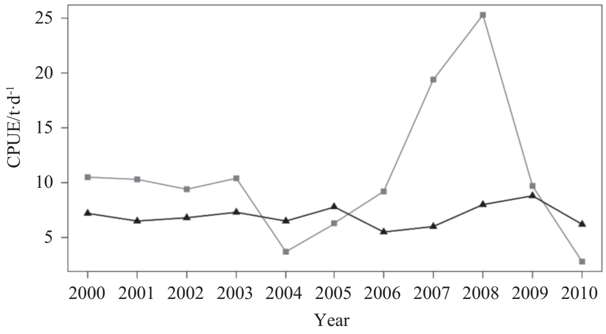

Fig. 1. Nominal CPUE and GLBM-standardized yearly CPUE for *I. argentinus* in Southwest Atlantic during 2000–2010. The gray rectangles represent nominal CPUE and the black triangles GLBM-standardized CPUE.

Table 4. Value of P_s on inferred hatching area in hatching months during 2000 to 2010 for *I. argentinus* in Southwest Atlantic

Year	P_s			*K* index
	June	July	August	
2000	0.39	0.30	0.32	0.95
2001	0.32	0.16	0.15	0.51
2002	0.22	0.19	0.22	0.62
2003	0.18	0.31	0.13	0.98
2004	0.22	0.20	0.20	0.64
2005	0.18	0.31	0.40	1.00
2006	0.17	0.19	0.30	0.62
2007	0.18	0.21	0.22	0.67
2008	0.22	0.26	0.08	0.85
2009	0.15	0.29	0.17	0.93
2010	0.14	0.28	0.26	0.90

Table 5. Correlations coefficients between the abundance index of *I. argentinus* and the monthly P_s during 2000–2010

Factor	*p*-value	*R*
P_s in June	>0.5	
P_s in July	<0.05	0.64
P_s in August	<0.8	–0.23

According to the posterior distribution of parameters (*r*, *K*, *q*) of two EDSP models (Figs 4 and 5), the big differences existed between posterior distribution of parameters and their prior distribution under uniform scenario. However, the posterior and prior distribution of *K* was similar under normal scenario, the posterior and prior distribution of *r* and *q* were different. The ranges of *r*, *K*, *q* were 0.65–1.33, 3 030 000–3 600 000 t, 0.02–0.03, respectively. Results suggested that the optimal model was the EDSP model for the minimum DIC value (Table 8) under the two scenarios.

The maximum sustainable yield (MSY) and its corresponding biomass (B_{MSY}) were 803 200 t and 1 515 500 t in the SP model under uniform distribution. The values of these two reference points under normal distribution were 1 163 800 t and 1 750 000 t, respectively. The MSY varied from 351 600 t to 685 100 t and B_{MSY} varied from 925 300 t to 1 803 000 t in the EDSP model under uniform distribution. While the MSY in the EDSP model under normal distribution varied from 287 400 t to 560 000 t and the B_{MSY} varied from 898 100 t to 1 720 300 t.

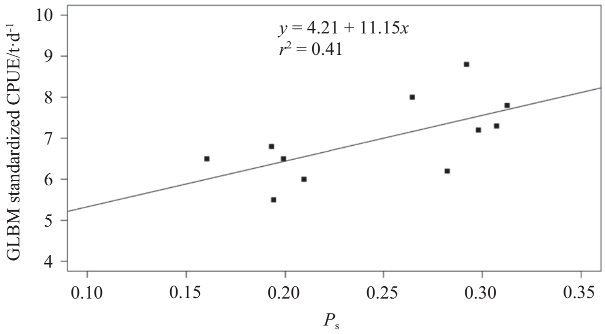

Fig. 2. Correlation between the proportion of the inferred hatching area occupied by favorable SST in July and GLBM-standardized CPUE for *I. argentinus*. The black line is regression line.

Table 6. Relationship between biomass of *I. argentines* and FMRP during 2000–2010 in EDSP model under uniform distribution

Year	Biomass/10^4 t	$B_{\mathrm{MSY}}/10^4$ t	MSY/10^4 t	$F_{0.1}$	F_{MSY}	F_{Year}
2000	250.00	171.92	65.33	0.34	0.38	0.21
2001	132.24	92.53	35.16	0.34	0.38	0.26
2002	138.16	111.36	42.32	0.34	0.38	0.13
2003	183.50	177.24	67.35	0.34	0.38	0.18
2004	179.15	114.85	43.64	0.34	0.38	0.01
2005	245.01	180.30	68.51	0.34	0.38	0.03
2006	219.16	111.99	42.55	0.34	0.38	0.13
2007	205.48	120.81	45.91	0.34	0.38	0.27
2008	201.87	152.66	58.01	0.34	0.38	0.20
2009	223.07	168.46	64.02	0.34	0.38	0.05
2010	266.04	162.83	61.88	0.34	0.38	0.04

Table 7. Relationship between biomass of *I. argentines* and FMRP during 2000–2010 in P_s-SP model under normal distribution

Year	Biomass/10^4 t	$B_{\mathrm{MSY}}/10^4$ t	MSY/10^4 t	$F_{0.1}$	F_{MSY}	F_{Year}
2000	250.00	166.87	53.40	0.29	0.32	0.21
2001	135.51	89.81	28.74	0.29	0.32	0.26
2002	133.33	108.08	34.59	0.29	0.32	0.14
2003	167.47	172.03	55.05	0.29	0.32	0.19
2004	162.04	111.47	35.67	0.29	0.32	0.02
2005	215.72	175.00	56.00	0.29	0.32	0.04
2006	208.37	108.69	34.78	0.29	0.32	0.14
2007	194.24	117.26	37.52	0.29	0.32	0.28
2008	182.88	148.17	47.41	0.29	0.32	0.22
2009	194.77	163.51	52.32	0.29	0.32	0.05
2010	232.71	158.05	50.58	0.29	0.32	0.04

Moreover, the values of $F_{0.1}$ and F_{MSY} were different in EDSP model under uniform and normal distribution (Tables 6 and 7). Based on the two surplus production models under two distributions, it was indicated that fishing mortality coefficient of *I. argentinus* from 2000 to 2010 was small than the values of $F_{0.1}$ and F_{MSY}. Meanwhile, annual catch of *I. argentinus* during 2000–2010 was also lower than the value of MSY (Tables 6 and 7).

4 Discussion

The role of environmental variables in regulating the dynamics of fish abundance has been a hot topic, in particular for short-lived species such as Ommstrephid squid (Roberts, 1998; Agnew et al., 2002). Most squid have less than 1-year lifespan (Boyle, 1987). With regard to short-lived species, recruitment success is greatly influenced by the physical and biological environmental

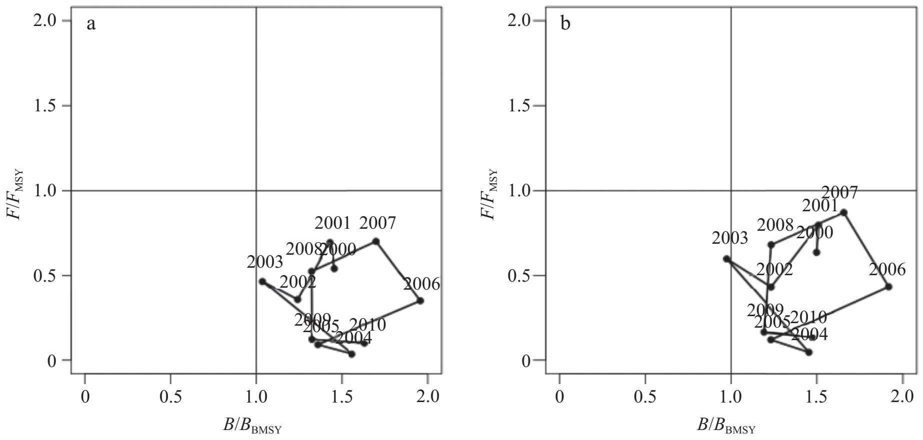

Fig. 3. Development of the *I. argentinus* fishery from 2000 to 2010 based on the SP model (a) and the EDSP model (b).

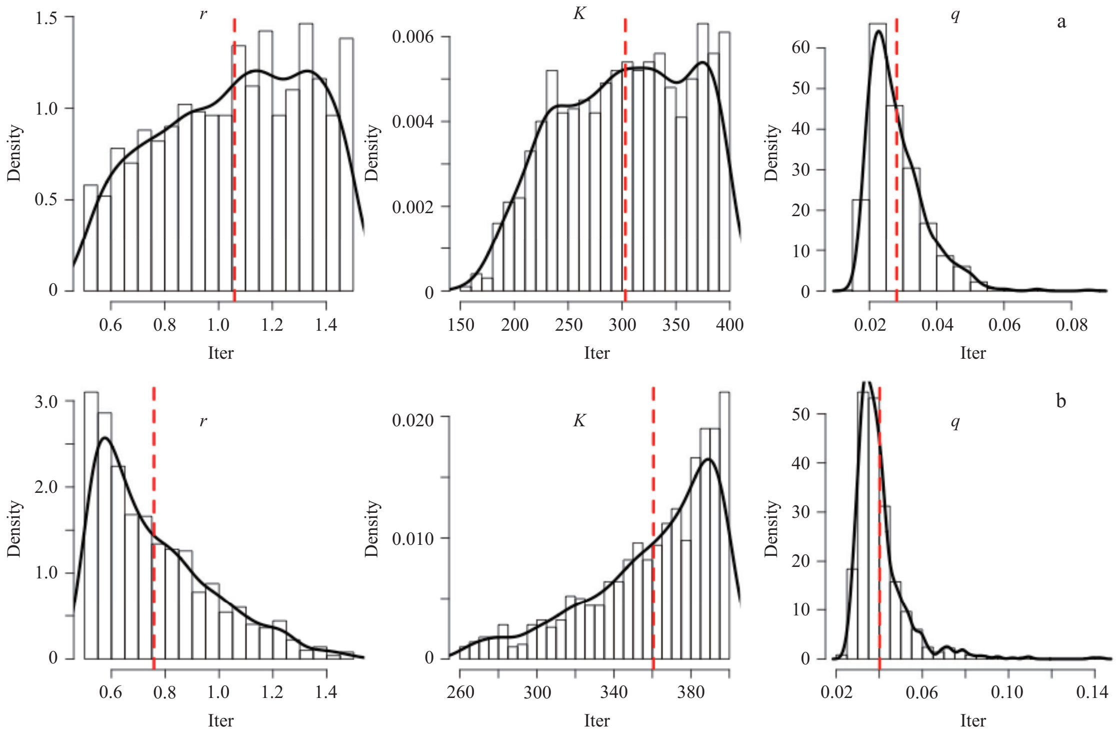

Fig. 4. Density for r, K and q in the SP model (a) and EDSP model (b) under uniform distribution scenario.

variables on the spawning and nursery grounds, and contributions to variations in the stock abundance (Sakurai et al., 2000). In addition, the abundance and distribution of squid populations tend to be greatly affected by oceanographic conditions and respond quickly to changes in the environment (Wadley and Lu, 1983; Waluda et al., 1999, 2001; Yatsu et al., 2000; Anderson and Rodhouse, 2001; Rodhouse, 2001; Bazzino et al., 2005). For example, Waluda et al. (2001) suggested that about 55% of the variability in recruitment of the Falkland Island *I. argentinus* fishery could be explained by variations in the total putative favorable-SST areas on the spawning ground during the spawning season. Variability in the abundance of *Todarodes pacificus* in the Sea of Japan was found to be closely related to changes in their favorable-SST areas for larvae development (Sakurai et al., 2000). Cao (2010) suggested that February P_{s} and August to November P_{f} (suitable SST in the presumed feeding grounds during the feeding seasons) could account for about 60% of the variability in *O. bartramii* abundance between 1995 and 2004, and February P_{s} was the most important period influencing squid recruitment during the spawning season, and feeding ground P_{f} during the fishing reason would also play a crucial influence on CPUE. Consequently, sea surface environmental indicators were important to use for predicting the recruitment of squid (Agnew et al., 2002). In this study, *I. argentinus* was a short-lived species with less than 1-year lifespan, the yearly biomass almost depended on recruitment. Therefore, it was reasonable to consider the environmental indices into the assessment of the *I. argentinus* stock. However, traditional surplus production model regards the carrying capacity as constant, which was inconsistent with the squid population dynamics. Therefore, we used P_{s} as an indicator of carrying capacity in this study, which were commonly utilized to evaluate the suitability of habitat on the spawning grounds.

Significant correlations were identified between yearly CPUE and monthly P_{s} in July, and this result was different from previ-

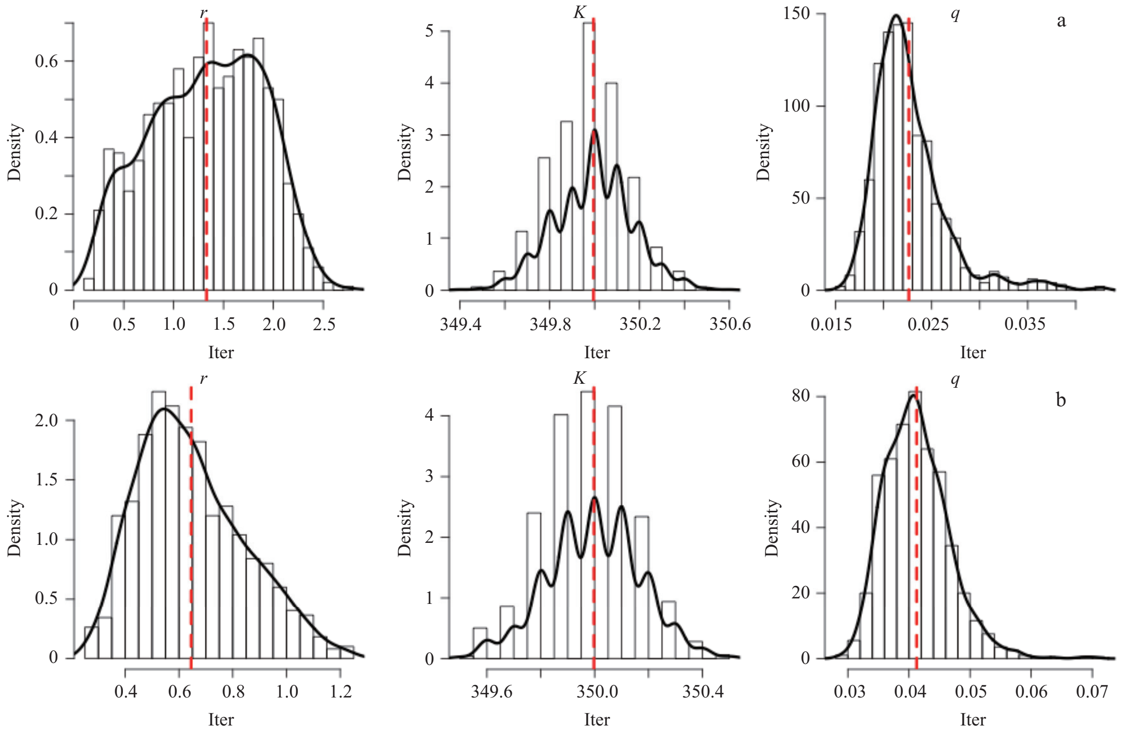

Fig. 5. Density for *r*, *K* and *q* in the SP model (a) and EDSP model (b) under normal distribution scenario.

Table 8. Summary statistics for the parameters of surplus production models for *I. argentines*

Parameter	Uniform distribution				Normal distribution			
	SP		EDSP		SP		EDSP	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
r	1.06	0.27	0.75	0.21	1.33	0.55	0.65	0.19
K	303	60.11	360.6	33.42	349	0.17	349	0.17
q	0.03	0.008	0.04	0.01	0.02	0.003	0.04	0.005
DIC	9.8		8.5		11.3		10.1	

ous findings (Waluda et al., 2001). The reason might be the use of various resources abundance indicators (nominal or standardized CPUE) and different sources of fishery data.

The methods to estimate parameters of surplus production model can be divided into three types including equilibrium estimators, process-error estimators, and observation-error estimators (Polacheck et al., 1993). Each estimator has its own drawbacks. For example, the assumption of equilibrium estimators is appropriate to apply to the fishery in equilibrium state, but it was not suitable for actual fishery. For process-error estimators, we usually obtain negative values of parameters (r, q) when converting surplus production equation into a linear form fitted by linear regression. Bayesian inference is increasingly used to fisheries in recent years, because it provides a systematic approach that explicitly incorporates both uncertainties and risk in the analysis (Hilborn et al., 1993; McAllister et al., 1994; Kinas, 1996; Chen et al., 2000). At the same time, atypical errors should be noted in the data. Mis-specification of prior distribution and the choice of an inappropriate likelihood function may result in unreliable posterior distribution for parameters in Bayesian inference (Berger et al., 1994; Adkison and Peterman, 1996; McAllister and Kirkwood, 1998; Chen et al., 2000). In this study, we used Bayesian inference to estimate the parameters of the two surplus production models under different settings, and we tried to make data consistent with the actual situation by standardizing yearly CPUE. We also referred to some of the previous studies in order to set the prior distribution (uniform and normal distribution) of parameters and to select likelihood function (Cao, 2010; Lu et al., 2013b). According to MCMC results, there were big differences in the posterior distributions of parameters (r, K, q) and prior distributions except the parameter of K under normal distribution. It was shown that fishery data of *I. argentinus* brought enough information for Bayesian inference.

According to the fishery data (Table 1), annual production of *I. argentinus* have greatly fluctuated. In this study, the annual catches of *I. argentinus* were lower than MSY and fishing mortality coefficient were also lower than $F_{0.1}$ in EDSP models under two scenarios, it was indicated that the resource of *I. argentinus* was not overfished. The yearly biomass of *I. argentinus* in EDSP models under two scenarios were all higher than B_{MSY}, which suggested that the resource of *I. argentinus* was at a high level in recent years. The results of this study were optimistic, and we could conclude that the resource of *I. argentinus* in the Southwest Atlantic did not suffer from overfishing, these findings were basically consistent with the previous results (Cao, 2010; Lu et al., 2013b).

The EDSP models were fitted well than SP models under uniform and normal scenarios by DIC values. It suggested that environmental conditions had significant influences on the parameter of carrying capacity. We obtained the changed values of fishery reference points in models with environmental factors. Those values could be more useful and preventive for managing *I. argentinus* fishery than fixed reference points.

The uncertainties of the models mainly came from the uncertainty of data collection and model parameters. (1) The catch data were only sourced from three parts included Chinese mainland, Taiwan of China and Falkland Islands in this study. (2) We assumed the biomass in 2003 to be initial resource with the value of 2 500 000 t, this assumption would cause biases on the estimation of biomass of *I. argentinus*. We also assumed that the standard deviation of CPUE (σ) was equal to 0.2, the effects of σ on model selection and resource assessment need to be studied in the future research.

In summary, the EDSP model fitted better than conventional Schaefer surplus model without environmental factors. We also estimated parameters of models and some fishery reference points based on spawning habitat of *I. argentinus* in Southwest Atlantic. These findings suggested that the environment of habitat should be considered in the squid stock assessment.

Acknowledgements

The authors thank Chinese distant-water Squid Jigging Technical Group for providing fishery data and information, and NOAA for providing environmental data used in this paper.

References

Adkison M D, Peterman R M. 1996. Results of Bayesian methods depend on details of implementation: an example of estimating salmon escapement goals. Fisheries Research, 25(2): 155–170

Agnew D J, Beddington J R, Hill S L. 2002. The potential use of environmental information to manage squid stocks. Canadian Journal of Fisheries and Aquatic Sciences, 59(12): 1851–1857

Anderson C I H, Rodhouse P G. 2001. Life cycles, oceanography and variability: ommastrephid squid in variable oceanographic environments. Fisheries Research, 54(1): 133–143

Arkhipkin A. 1993. Age, growth, stock structure and migratory rate of pre-spawning short-finned squid *Illex argentinus* based on statolith ageing investigations. Fisheries Research, 16(4): 313–338

Arkhipkin A I. 2000. Intrapopulation structure of winter-spawned Argentine shortfin squid, *Illex argentinus* (Cephalopoda, Ommastrephidae), during its feeding period over the Patagonian Shelf. Fishery Bulletin, 98(1): 1–13

Arkhipkin A, Laptikhovsky V. 1994. Seasonal and interannual variability in growth and maturation of winter-spawning *Illex argentinus* (Cephalopoda, Ommastrephidae) in the Southwest Atlantic. Aquatic Living Resources, 7(4): 221–232

Basson M, Beddington J R, Crombie J A, et al. 1996. Assessment and management techniques for migratory annual squid stocks: the *Illex argentinus* fishery in the Southwest Atlantic as an example. Fisheries Research, 28(1): 3–27

Bazzino G, Quiñones R A, Norbis W. 2005. Environmental associations of shortfin squid *Illex argentinus* (Cephalopoda: Ommastrephidae) in the Northern Patagonian Shelf. Fisheries Research, 76(3): 401–416

Berger J O, Moreno E, Pericchi L R, et al. 1994. An overview of robust Bayesian analysis. Test, 3(1): 5–124

Bigelow K A, Boggs C H, He X. 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fisheries Oceanography, 8(3): 178–198

Boyle P R. 1987. Cephalopod Life Cycles, Vol. II, Comparative Reviews. London: Academic Press

Brunetti N E, Ivanovic M, Rossi G, et al. 1998. Fishery biology and life history of *Illex argentinus*. In: Okutani T, ed. Contributed Papers to International Symposium on Large Pelagic Squids. Tokyo: Japan Marine Fishery Resources Research Center, 217–231

Cao Jie. 2010. Stock assessment and risk analysis of management strategies for neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean (in Chinese) [dissertation]. Shanghai: Shanghai Ocean University

Chen Yong, Breen P A, Andrew N L. 2000. Impacts of outliers and mis-specification of priors on Bayesian fisheries-stock assessment. Canadian Journal of Fisheries and Aquatic Sciences, 57(11): 2293–2305

Chen Xinjun, Chen Yong, Tian Siquan, et al. 2008. An assessment of the west winter-spring cohort of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean. Fisheries Research, 92(2-3): 221–230

Chen C S, Chiu T S. 2009. Standardising the CPUE for the *Illex argentinus* fishery in the Southwest Atlantic. Fisheries Science, 75(2): 265–272

Haimovici M, Brunetti N E, Rodhouse P G, et al. 1998. Illex argentinus. In: Rodhouse P G, Dawe E G, O'Dor P K, eds. Squid Recruitment Dynamics: The Genus *Illex* as a Model, The Commercial *Illex* Species and Influences on Variability (FAO Fisheries Technical Paper 376). Rome: FAO, 27–58

Haimovici M, Santos R A D, Bainy M C R S, et al. 2014. Abundance, distribution and population dynamics of the short fin squid *Illex argentinus* in Southwestern and Southern Brazil. Fisheries Research, 152: 1–12

Hatanaka H. 1998. Feeding migration of short-finned squid *Illex argentinus* in the waters off Argentina. Nippon Suisan Gakkaishi, 54(8): 1343–1349

Hilborn R, Pikitch E K, Francis R C. 1993. Current trends in including risk and uncertainty in stock assessment and harvest decisions. Canadian Journal of Fisheries and Aquatic Sciences, 50(4): 874–880

Hilborn R, Walters C J. 1999. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. London: Chapman & Hall.

Ichii T, Mahapatra K, Okamura H, et al. 2006. Stock assessment of the autumn cohort of neon flying squid (*Ommastrephes bartramii*) in the North Pacific based on past large-scale high seas driftnet fishery data. Fisheries Research, 78(2-3): 286–297

Kinas P G. 1996. Bayesian fishery stock assessment and decision making using adaptive importance sampling. Canadian Journal of Fisheries and Aquatic Sciences, 53(2): 414–423

Li Gang, Chen Xinjun, Guan Wenjiang, et al. 2011. Stock Assessment and Management for *Mackerel* in East Yellow Sea (in Chinese). Beijing: Science Press, 4–128

Lu Huajie, Chen Xinjun, Cao Jie, et al. 2013a. CPUE standardization of *Illex argentinus* for Chinese Mainland squid-jigging fishery in the southwest Atlantic Ocean. Journal of Fisheries of China (in Chinese), 37(6): 951–960

Lu Huajie, Chen Xinjun, Li Gang, et al. 2013b. Stock assessment and management for *Illex argentinus* in Southwest Atlantic Ocean based on Bayesian Schaefer model. Chinese Journal of Applied Ecology (in Chinese), 24(7): 2007–2014

Maunder M N, Punt A E. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research, 70(2-3): 141–159

McAllister M K, Kirkwood G P. 1998. Bayesian stock assessment: a review and example application using the logistic model. ICES Journal of Marine Science, 55(6): 1031–1060

McAllister M K, Pikitch E K, Punt A E, et al. 1994. A Bayesian approach to stock assessment and harvest decisions using the sampling/importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences, 51(12): 2673–2687

Osako M, Murata M. 1983. Stock assessment of cephalopod resources in the northwestern Pacific. In: Caddy J F, ed. Advances in Assessment of World Cephalopod Resources. FAO Fisheries Technical Paper. 55–144

Polacheck T, Hilborn R, Punt A E. 1993. Fitting surplus production models: comparing methods and measuring uncertainty. Canadian Journal of Fisheries and Aquatic Sciences, 50(12): 2597–2607

Prager M H. 1994. A suite of extensions to a non-equilibrium surplus-production model. Fishery Bulletin, 92(2): 374–389

Roberts M J. 1998. The influence of the environment on chokka squid *Loligo vulgaris reynaudii* spawning aggregations: steps towards a quantified model. South African Journal of Marine Science, 20(1): 267–284

Rodhouse P G. 2001. Managing and forecasting squid fisheries in variable environments. Fisheries Research, 54(1): 3–8

Rosas-Luis R, Sánchez P, Portela J M, et al. 2014. Feeding habits and trophic interactions of *Doryteuthis gahi*, *Illex argentinus* and *Onykia ingens* in the marine ecosystem off the Patagonian Shelf. Fisheries Research, 152: 37–44

Sakurai Y, Kiyofuji H, Saitoh S, et al. 2000. Changes in inferred spawning areas of *Todarodes pacificus* (Cephalopoda: Ommastrephidae) due to changing environmental conditions. ICES Journal of Marine Science, 57(1): 24–30

Wadley V A, Lu C C. 1983. Distribution of mesopelagic cephalopods around a warm-core ring in the East Australian Current. Memoirs of the National Museum of Victoria, 44(1): 197–198

Waluda C M, Griffiths H J, Rodhouse P G. 2008. Remotely sensed spatial dynamics of the *Illex argentinus* fishery, Southwest Atlantic. Fisheries Research, 91(2-3): 196–202

Waluda C M, Rodhouse P G, Podestá G, et al. 2001. Surface oceanography of the inferred hatching grounds of *Illex argentinus* (Cephalopoda: Ommastrephidae) and influences on recruitment variability. Marine Biology, 139(4): 671–679

Waluda C M, Trathan P N, Rodhouse P G. 1999. Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda: Ommastrephidae) fishery in the South Atlantic. Marine Ecology Progress Series, 183: 159–167

Wang Shengping, Maunder M N, Aires-da-Silva A. 2014. Selectivity's distortion of the production function and its influence on management advice from surplus production models. Fisheries Research, 158: 181–193

Wang Jintao, Yu Wei, Chen Xinjun, et al. 2016. Stock assessment for the western winter-spring cohort of neon flying squid (*Ommastrephes bartramii*) using environmentally dependent surplus production models. Scientia Marina, 80(1): 69–78

Yatsu A, Watanabe T, Mori J, et al. 2000. Interannual variability in stock abundance of the neon flying squid, *Ommastrephes bartramii*, in the North Pacific Ocean during 1979-1998: impact of driftnet fishing and oceanographic conditions. Fisheries Oceanography, 9(2): 163–170

Zhan Bingyi. 1995. Fishery Stock Assessment (in Chinese). Beijing: China Agriculture Press, 170–180