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EVALUATING THE UNCERTAINTY OF THE POPULATION GROWTH PARAMETER ESTIMATES OF LARVAL ANCHOVY IN THE SOUTHWESTERN WATERS OF TAIWAN USING MONTE CARLO SIMULATIONS

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Key words: larval anchovy, population growth parameter, Monte Carlo simulation, uncertainty, southwestern waters of Taiwan.

ABSTRACT

To estimate the population growth parameter (maximum sustainable yield, carrying capacity, catchability, the ratio of initial biomass to carrying capacity and model shape parameter) of larval anchovy in the southwestern waters of Taiwan, a non-equilibrium production model was used to fit to historical catch data and standardized CPUE series. The results of standardized CPUE indicated that the sea surface temperature was the most effective variable for explaining the CPUE variation of larval anchovy abundance. This study also evaluated impact of the uncertainty associated with the catch and CPUE data on the model estimations using Monte Carlo simulations. Although the impacts of the uncertain data on the accuracy of model estimations were minor, the precision of estimations would be deteriorated if the level of errors in the data source, particularly for CPUE data, was increased. In addition, the assumption of Schafer's logistic production model would be more appropriate than Fox's model which was applied to larval anchovy in the southwestern waters of Taiwan in previous study.

I. INTRODUCTION

The population of larval anchovy in the southwestern waters of Taiwan mainly consists of *Engraulis japonica*, *Encrasicholina punctifer* and *Enc. heteroloba* [28]. In the southwestern waters of Taiwan near the city of Fangliao (Fig. 1), two-boat trawling was introduced in 1979 and this fishery has rapidly expanded and replaced traditional types of fishing gear, such as torch-light net, beach seine, and set net since 1981 [13]. However, as these three species of larval anchovy are harvested by the same fishing gear on the same fishing grounds and in the same fishing seasons, they have been combined as the larval anchovy stock [1, 2, 14-16, 28]. Fig. 2 shows the effort and catch of anchovy caught from the southwestern waters of Taiwan from 1980 to 2007 and it indicated that annual total catches and efforts are significantly varied from 68 to 1032 tons and 496 to 2702 day-vessels, respectively. The annual catches of larval anchovy between 1981 and 1988, varying between 300-600 tons, except for very

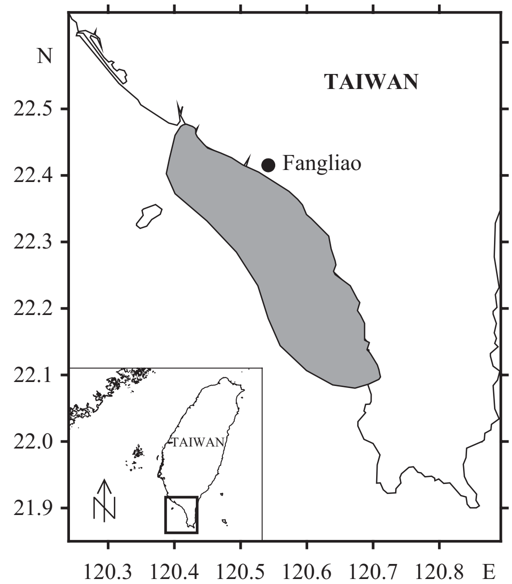

Fig. 1. The study area (shaded) for the larval anchovy in the southwestern waters of Taiwan.

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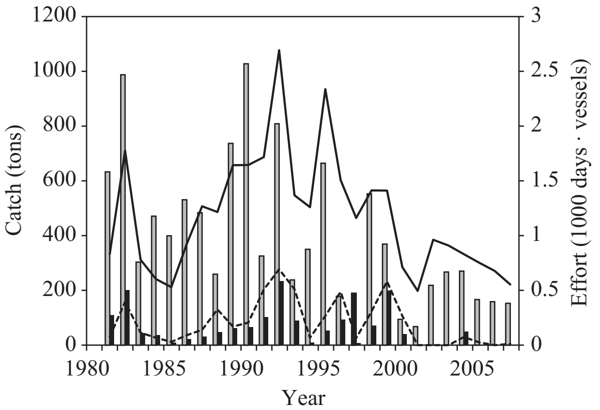

Fig. 2. Time series of total catch (gray bars), catch from June and August (black bars), total fishing effort (solid line) and fishing effort from June to August (dashed line) of larval anchovy fishery in the southwestern waters of Taiwan.

high catch recorded in 1982. In 1989 and 1990, the catches substantially increased and reached the historical peak in 1990. Thereafter, the annual catches have fluctuated with apparent decreasing tendency and decreased to about 200 tons in recent years.

Some previous studies have been conducted to explore the relationships between abundance and environmental conditions. Tsai *et al*. [28] also investigated the correlations between relative abundance (catch per unit effort, CPUE) and environmental conditions for this stock, and inferred that the fluctuations of larval anchovy abundance were determined by local sea surface temperature (SST) and were related to the Southern Oscillation Index (SOI). Hsieh *et al*. [10] investigated environmental effects on larval anchovy fluctuations and the results indicated the correlation between abundance and SST was transient and simply reflected El Nino Southern Oscillation (ENSO). They also indicated the decline of larval anchovy during ENSO may be due to reduced China Coastal Current.

Due to the low catch levels in recent years, it is necessary to investigate the impact of fishery exploitation on the population dynamics for management purpose. However, larval anchovy is a resource with short lifespan and without catch-at-size or catch-at-age data. Since historical catch and effort were available, the population growth parameters of larval anchovy in the southwestern waters of Taiwan could be estimated through catch-per-unit-effort (CPUE) analysis and the surplus production models (e.g. Schaefer [26, 27] and Fox [4]). Tsai *et al*. [29] have evaluated the effects of fishing effort on stock size and catch of larval anchovy in the coastal waters of southwestern Taiwan using univariate autoregressive integrated moving average model, transfer function noise model and equilibrium surplus production model (Fox model).

However, the traditional surplus production models assumed that the stock is in equilibrium condition while the exploited stocks are rarely in equilibrium. Previous studies also suggested that non-equilibrium production model estimators, which are based on the assumptions that the population dynamics are deterministic and that all errors occurs in the relationship between the model quantities and the observed data, perform better than most other variants, including the classical equilibrium approaches [20, 25]. In addition, catch and CPUE are the key input data for surplus production model and the uncertainty of these data would influence the estimation of the model.

Therefore, this study attempted to evaluate the influences of the uncertainty associated with catch and CPUE data on population growth parameters of larval anchovy in the southwestern waters of Taiwan by using Monte Carlo simulation approach. The estimates the population growth parameters were estimated by fitting the non-equilibrium production model [21] to the historical catch and standardized CPUE data.

II. MATERIALS AND METHODS

1. Data Used

Monthly catch in weight (kg) and effort (day-vessels) data of larval anchovy fishery in the southwestern waters of Taiwan from January 1981 to December 2007 was obtained from the Fangliao Fisherman Association. The effort data of January 2007 was not available and thus the CPUE data of this month was excluded from the analysis of CPUE standardization.

Aggregated monthly satellite-derived AVHRR (advanced very high resolution radiometer) sea surface temperature (SST) data of $0.5° \times 0.5°$ square (22~22.5°N, 119.25~119.75°E), including mean, standard deviation and deviation from mean (SSTA), from January 1981 to December 2007 were obtained from the IRI/LDEO Climate Data Library (http://ingrid.ldgo.columbia.edu/expert/SOURCES/IGOSS/). The values of SOI were obtained from the National Center for Atmospheric Research, USA (http://www.cgd.ucar.edu/cas/catalog/climind/soi.html). The data of salinity were obtained from the Taiwan Fisheries Research Institute.

2. CPUE Standardization

The nominal CPUE (defined as the catch in weight per day-vessel) was standardized using a general linear model (GLM) [5, 7, 12], with the assumption that the errors are log-normally distributed. The main effects considered in this analysis were year (Y), month (M), SST, SSTA, SOI and salinity. The effects of Y and M were treated as category variables and the effects of SST, SSTA, SOI and salinity were treated as continuous variables. Because high autocorrelation would occur among environmental effects, the interactions between effects were not considered in the GLM. The estimation of the log-transformed model was based on the Gaussian probability density function and the identity as the link function.

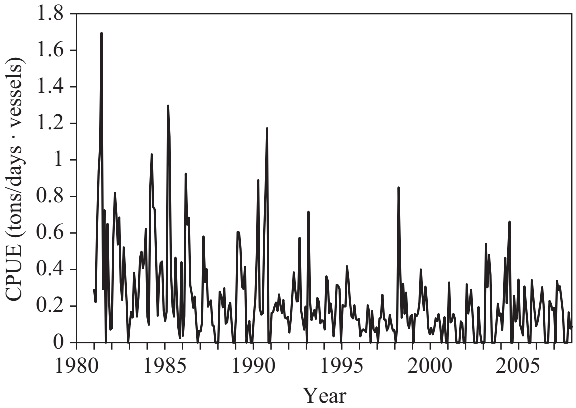

Fig. 3. Time series of monthly nominal CPUE of larval anchovy fishery in the southwestern waters of Taiwan.

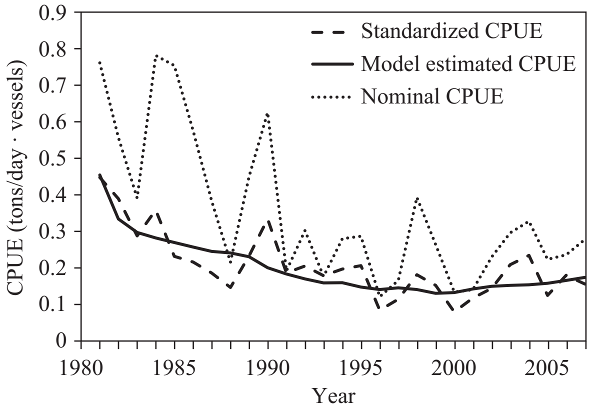

Fig. 4. Time series of nominal, standardized and model estimated CPUE of larval anchovy fishery in the southwestern waters of Taiwan.

$$\begin{aligned}&\log(\text{CPUE}) = \text{Y} + \text{M} + \text{SST} + \text{SSTA} + \text{SOI} + \text{Salinity} + \varepsilon \\ &\varepsilon \sim N(0, \sigma^2)\end{aligned} \tag{1}$$

In this study, yearly time scale was adopted to explore the trend of standardized CPUE instead of monthly scale that was commonly used for previous studies, and this facilitates the representation of CPUE pattern (Fig. 3 and Fig. 4). The annual standardized CPUEs were computed from the adjusted means (i.e. least square means or marginal means defined by SAS Institute Inc.) of the estimates of the year effect [7]. The GLM analysis was conducted using R version 2.13.2 (The R Development Core Team, 2011).

3. Population Growth Parameter Estimates

The parameters of the maximum sustainable yield (*MSY*), carrying capacity (*K*), catchability (*q*), the ratio of initial biomass to *K* (B_1/K) and model shape parameter (the ratio of biomass at *MSY* level to *K*, $\phi = B_{MSY}/K$) were selected to explore the influences of uncertainty associated with catch and CPUE data on model estimates.

The estimations were implemented using computer program of A Stock-Production Model Incorporating Covariates (ASPIC version 5 [22]) with the direct optimization method. The non-equilibrium surplus production model [21] was used to estimate the population growth parameters and the generalized model developed by Pella and Tomlinson [19] and restructured by Fletcher [3] was adopted in this study. The method adopted in this study included the estimation conditional on observed catch, assuming lognormal observation error in catch, and the parameters of the models were estimated by minimizing the objective function, which is the sum of squared residuals in the logarithm of the relative abundance index (i.e. standardized CPUE in this study).

4. Evaluating Uncertainty Using Simulation

The influences of the uncertainty associated with catch and CPUE data on model estimates were performed using the Monte Carlo simulation method. The observed catch and standardized CPUE data sets are assumed to be the "true" data and the artificial data sets were generated by adding the noises to the "true" catch (C_t) and CPUE (I_t) data [31]. Based on the approach of Wang *et al*. [31], the simulated catch data (C_t') are generated by adding log-normally distributed observation error (v_C; $v_C \sim N(0, \sigma_C^2)$) to the "true" catch data:

$$C_t' = C_t e^{v_C - \sigma_C^2/2} \tag{2}$$

The simulated CPUE data (I_t') are generated by adding log-normally distributed observation error (v_I; $v_I \sim N(0, \sigma_I^2)$) to the "true" CPUE data:

$$I_t' = I_t e^{v_I - \sigma_I^2/2} \tag{3}$$

The production model was then fitted to the simulated data sets to provide the estimates of the quantities of interests. The sensitivity of the results to all combinations of three levels of error when quantifying the catch and CPUE was examined (σ_C and σ_I were set to be 0.01, 0.05 and 0.10, separately). A total of 100 simulation runs was conducted for each data set with a specific level of error.

The influence of uncertain data on the estimates of the model was quantified for each Monte Carlo replicate and parameter by the relative error [25, 31]:

$$E_i^j = \frac{\hat{Q}_i^j - Q^j}{Q^j} \times 100 \tag{4}$$

where E_i^j is the relative error (%) for simulation *i* and parameter *j*, $\hat{Q}_i^j$ is the value for simulation *i* and parameter *j* provided by the estimation model, and Q^j is the value for parameter *j* obtained by fitting the model to the "true" data.

Table 1. Analysis of variance table for GLM analysis for CPUE of larval anchovy fishery in the southwestern waters of Taiwan.

(A) The summary for the model

Source	Degree of freedom	Sum of squares	Mean squares	F-value	*P*-value
Model	41	76.84	1.8743	5.62	< 0.0001
Error	235	78.32	0.3333		
Total	276.00	155.1691			

(B) The summary for effects

Variable	Degree of freedom	Sum of squares	Mean squares	F-value	*P*-value
Y	26	44.48	1.7109	5.13	< 0.0001
M	11	29.72	2.7017	8.11	< 0.0001
SST	1	1.44	1.4426	4.33	0.0386
SSTA	1	1.29	1.2897	3.87	0.0500
SOI	1	0.69	0.6944	2.08	0.1502
Salinity	1	1.03	1.0346	3.10	0.0794

The median of relative error (MRE) and inter-quartile range (IQR) of relative error were used to explore the accuracy and precision of parameter estimates obtained from various levels of observation errors [31].

III. RESULTS

1. Analysis of CPUE Standardization

Based on the results of GLM analysis, it is obvious that the year and month effects are the most influential variables on CPUE variation and they explained about 48% of total variance (Table 1). This is not surprising because there are apparent yearly trend and seasonal fluctuation in CPUE (Fig. 3 and Fig. 4). However, the explanation abilities of hydrographic effects on CPUE variation are much lower than year and month effects and they explained 0.45% to 0.93% of total variance even though the SST effects is statistically significant (Table 1). The effects of SOI and Salinity were eliminated in final GLM for obtaining the standardized CPUE.

Annual nominal and standardized CPUE are shown in Fig. 4. The trend of nominal CPUE obviously fluctuated with a decline pattern before 1996, in which the standardized CPUE decreased to lowest value than ever, and fluctuated with a slightly increasing pattern thereafter. Standardized CPUE generally follows the trend of nominal CPUE but it represents a relatively apparent trend with lower fluctuation, particularly for the time series before early 1990s.

Fig. 5 represents the comparison between the annual trend of standardized CPUE and the annual trends of hydrographic variables used in CPUE standardization. The results reveal apparent patterns between standardized CPUE and the variables related SST. Before 1996, the decline of standardized CPUE generally accompanied the increase of SST, and lower values of CPUE also occurred in the year with higher SST. Nevertheless, the peaks of standardized CPUE appeared to occur in the years with peaks of SST and SSTA since 1996.

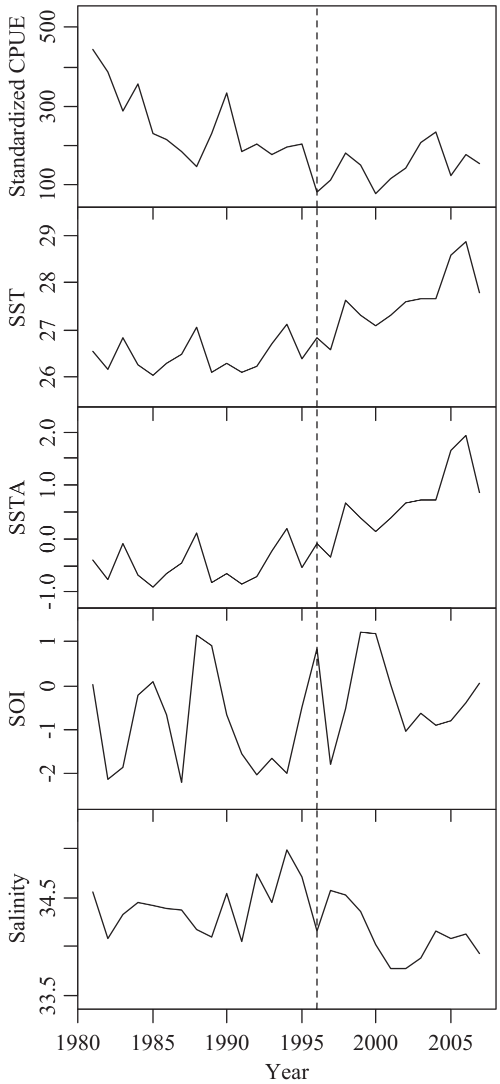

Fig. 5. Annual trends of standardized CPUE of larval anchovy, SST, SSTA, SOI and Salinity in the southwestern waters of Taiwan. Dashed line shows the year of 1996.

Table 2. Median relative error (MRE) and inter-quartile range (IQR; values in parentheses) of the relative errors (%) for population growth parameter estimates corresponding to various levels of observation errors associated with catch and CPUE data. σ_C and σ_I were the standard deviations of the random observation errors for catch and CPUE data.

		ϕ (B_{MSY}/K)	B_1/K	MSY	K	q
σ_C						
	0.01	0.0	-0.5	0.0	0.0	0.0
		(0.2)	(1.0)	(0.6)	(1.3)	(1.8)
	0.05	0.0	-0.6	0.3	0.2	0.0
		(0.6)	(2.5)	(3.2)	(6.5)	(8.0)
	0.1	0.0	-1.1	-0.4	0.2	-0.1
		(1.4)	(6.5)	(5.4)	(12.6)	(17.4)
σ_I						
	0.01	0.0	-1.0	-0.1	0.2	-0.3
		(0.5)	(4.2)	(1.5)	(2.2)	(3.6)
	0.05	-0.8	0.7	-1.1	2.5	-3.5
		(2.9)	(18.3)	(7.2)	(9.6)	(12.7)
	0.1	-1.8	-1.0	-2.2	4.4	-6.0
		(5.8)	(34.8)	(13.7)	(21.6)	(30.7)

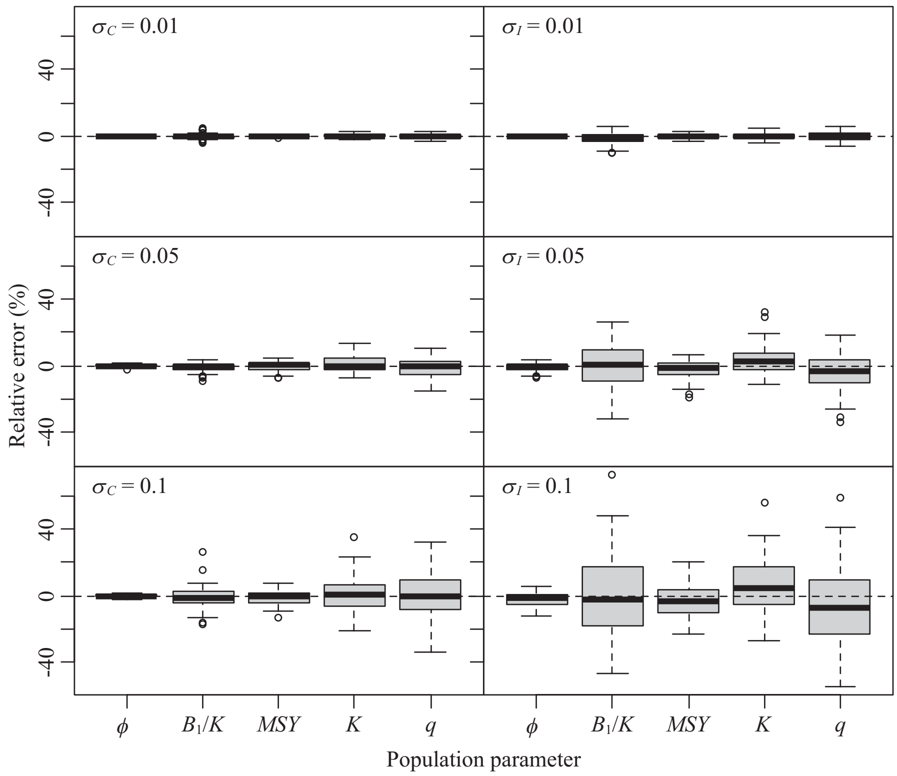

Fig. 6. Box plots of the relative errors (%) for population growth parameter estimates corresponding to various levels of observation errors associated with catch (left) and CPUE (right) data. The centerline represents the median and the box represents the quartiles. The whiskers extend 1.5 times the inter-quartile range.

Although SOI fluctuated with indistinct trend and cannot explain the variance of CPUE very well, higher SOI generally led to lower CPUE. There is no apparent trend in salinity but the CPUE trend roughly fluctuated with the inverse pattern of salinity before 1996 and then followed the salinity trend thereafter.

2. Impact of Data Uncertainty on Population Growth Parameter Estimates

Fig. 6 and Table 2 show the distributions, MRE and IQR of the relative errors for parameter estimates corresponding to various levels of observation errors associated with catch and CPUE data. As expected, the parameter estimates were al-most identical to the true values when $\sigma_C = 0.01$ (MREs were quite close to 0 and IQRs were between 0.15 and 1.8%). Although the impact of a low level of observation error in the CPUE data ($\sigma_I = 0.01$) was minor, the accuracy and imprecision of estimates were slightly worse than those from the assumption of the lowest level of error in catches (MREs between -1.0 and 0.2%, and IQRs were between 0.5 and 4.2%). Estimation error remained good (MREs between -0.6 and 0.3%, and IQRs between 0.6 and 8.0%) when $\sigma_C = 0.05$, but the estimates were somewhat biased (MREs between -3.5 and 2.5%) and the imprecision of the estimates deteriorated obviously (IQRs between 2.9 and 18.3%) when $\sigma_I = 0.05$. When $\sigma_C = 0.1$, the estimates of parameters were still unbiased (MREs between -1.1 and 0.24%) but the precisions of estimations were slightly degenerative (IQRs between 1.4 and 17.4%). When $\sigma_I = 0.1$, however, the accuracy of estimations were evidently deteriorated (MREs between -6.0 and 4.4%) and the estimations were also highly imprecise (IQRs between 5.8 and 34.8%).

The results of simulation analysis indicate that the model shape parameter was the most robust parameter ($\phi = B_{MSY}/K \approx 0.66$) despite observation errors were added to catch or CPUE data. The estimate of *MSY* remained accurate when adding observation errors to catch or CPUE data, while increasing the observation errors in CPUE data lead to the imprecise estimate of *MSY*. The estimates of K, q and B_1/K were substantially sensitive to the observation errors in catch and CPUE data. In particular, increasing observation error in CPUE data not only lead to biased estimates for these parameters but also substantially deteriorated the precision of these parameters (Fig. 6 and Table 2).

IV. DISCUSSION

Tsai *et al*. [29] illustrated the historical yields and efforts against optimal yield (MSY) and fishing effort (f_{MSY}) for 1980-1992 based on the Fox's equilibrium production model and their results indicated that historical fishing exploitation was lower than the optimal level (yield and effort were less than MSY and f_{MSY}) except for the early 1980s and the period between late 1980s and early 1990s when the yield exceeded the MSY level. With increasing awareness of the vulnerability of natural resources, it is interesting to see the effects of the 3-months (June to August) closure period of fishery regulation for larval anchovy to reduce the exploitation and discard in fishery since 2001. This fishery policy of fishing closure is similar to the input control regulation which attempts to limit fishing effort by controlling the capacity of fleets (structural measures) and time spent at sea. However, many previous studies indicated that the uncertainties of the model structure and data should be evaluated prior to the stock assessment (e.g. [11], [30] and [31]). Therefore, this study did not attempt to explore the population status of larval anchovy in the southwestern waters of Taiwan but focused on the evaluating the impact of the uncertainty in input data of the model on the estimates of population growth parameters.

In this study, population growth parameters were estimated by fitting the generalized non-equilibrium surplus production model to the catch and standardized CPUE data. However, it is difficult to verify exactly the correctness of catch and CPUE data. For instance, standardized CPUEs are usually included in stock assessments as relative indices of abundance. In this study, the effect of SST did not substantially improve the explanation of variance of CPUE when conducting the CPUE standardization analysis even though this effect was statistically significant (Table 1). Previous studies indicated that the abundance of larval anchovy in the southwestern waters of Taiwan is also significantly correlated with the environmental conditions, such as SST and southern oscillation index (SOI) [15, 28]. Hsieh *et al*. [10] suggested that the main factor which caused the interannual variation of anchovy CPUE might change through time. Several previous studies on this population also emphasized that the fluctuations of larval anchovy abundance were determined by local SST and anomaly [8, 9, 16, 28], which in turn were related to the SOI [28]. The standardized CPUE appears to reveal reverse trends in the periods prior and after 1996 (Fig. 5). However, the CPUE trends did not obviously accompany the trends of environmental effects except for salinity. Hsieh *et al*. [10] indicated that the CPUE showed a positive correlation with river runoff. Therefore, the invers CPUE trends could be further investigated with the changes in salinity effect and its relevant environmental conditions, such as river runoff.

Hsieh *et al*. [10] speculated that the seasonal strength of the anchovy CPUE is significantly related to the fraction of the *Eng. japonicus*, particularly in the major fishing season (spring). Lee *et al*. [14] also indicated that the catches of larval anchovy increased when *Eng. japonicus* was the dominant species during the year of low SST. However, about 55% decline in catches occurred as the result of anomalies of rising water temperature resulted in the dominance of the genus *Encrasicholina* [28]. Obviously, there is a relationship between the abundance of anchovy larvae and the species of dominance in the southwestern waters of Taiwan, where is strongly influenced by the SST [15, 28]. That correlation may be transient and simply a reflection of ENSO signals [10].

In addition, we are unable to know the correct values of the population growth parameters. One way to overcome these problems is to test the estimation performance by means of Monte Carlo simulation [6, 20]. This study examined the impact of uncertainty in catch and CPUE data on the estimations of the assessment model for larval anchovy in the southwestern waters of Taiwan using the Monte Carlo simulation. The results indicate that the estimates of population growth parameters selected in this study were close to be unbiased when incorporating observation errors for catch and CPUE data. However, the precision of estimations deteriorates when the level of errors in the data source increases, particularly for the CPUE data (Fig. 6 and Table 2). In contrast, the impact of uncertainty in catch data on the estimations of the assessment model is relatively minor.

Prager [22] indicated that the generalized model would be equivalent to Schafer's logistic production model [26, 27] if shape parameter ϕ = 0.5, and the model would be close to Fox's model [4] if $\phi \approx 0.3679$. Among the parameters estimated in this study, the model shape parameter was the most robust and the estimate indicated that the Schafer's logistic production model would be more appropriate for larval anchovy in the southwestern waters of Taiwan rather than Fox's production model adopted by Tsai *et al*. [29]. This result implied that the assumption of model structure used in previous study should be reconsidered for further assessment. In contrast, the estimates of K, q and B_1/K were obviously sensitive to the observation errors. Prager [21] and Prager *et al*. [23] indicated that absolute levels of stock biomass and related quantities, which included uncertainty in the estimate of q, were usually estimated much less precisely. In addition, the starting biomass, estimated as B_1/K, may be considered a nuisance parameter, and its estimate is often imprecise Prager [22]. Punt [24] recommended fixing B_1/K =1 rather than estimating it for the Cape hake stock off southern Africa but this might not be appropriate for every stock. For further management purpose, however, several previous studies also indicated that relative quantities, such as the ratio of fishing mortality to that at MSY level (F/F_{MSY}) and the ratio of biomass to that at MSY level (B/B_{MSY}), were relatively accurate and precise [21, 31].

The results of this study and previous [17, 18] indicated that reliable indices of abundance play a key role in tuning analytical stock assessments. Fishery-independent survey index would be a better alternative representation of relative abundance. In practice, CPUE standardization consists of the process used to remove biases and produce a reliable index of abundance [17]. To date, therefore, reliable index obtained by linking the fishery-dependent data (i.e. catch and effort) with environmental conditions would be helpful to improve the precision of population growth parameter estimates for larval anchovy in the southwestern waters of Taiwan. In addition, Hsieh *et al*. [10] suspect that the reduced strength of the China Coastal Current might be the key parameter for the fluxes of Japanese anchovy populations toward Taiwan. Therefore, it will be advantageous to combine the field survey information such as the data of the Taiwan Cooperative Oceanic Fisheries Investigation (TaiCOFI) [32] in the future.

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