A Comparative Analysis of Surplus Production Models and a Maximum Entropy Model for Estimating the Anchovy's Stock in Korea

Hee-Dong PYO
Pukyung National University

우리나라 멸치자원량 추정을 위한 잉여생산모델과 최대엔트로피모델의 비교분석

표 희 동
(부경대학교)

(Received March 18, 2006 / Accepted March 31, 2006)

Abstract

For fishery stock assessment and optimum sustainable yield of anchovy in Korea, surplus production(SP) models and a maximum entropy(ME) model are employed in this paper. For determining appropriate models, five traditional SP models-Schaefer model, Schnute model, Walters and Hilborn model, Fox model, and Clarke, Yoshimoto and Pooley (CYP) model-are tested for effort and catch data of anchovy that occupies 7% in the total fisheries landings of Korea. Only CYP model of five SP models fits statistically significant at the 10% level. Estimated intrinsic growth rates are similar in both CYP and ME models, while environmental carrying capacity of the ME model is quite greater than that of the CYP model. In addition, the estimated maximum sustainable yield(MSY), 213,287 tons in the ME model is slightly higher than that of CYP model (198,364 tons). Biomass for MSY in the ME model, however, is calculated 651,000 tons which is considerably greater than that of the CYP model (322,881 tons). It is meaningful in that two models are compared for noting some implications about any significant difference of stock assessment and their potential strength and weakness.

Key words: *Fishery stock assessment, Surplus production(SP) models, Maximum entropy(ME) model, anchovy*

---

† Corresponding author : 051-620-6519, pyoh@pknu.ac.kr

* 이 논문은 2002학년도 부경대학교 동원학술연구재단의 지원에 의하여 연구되었으며, 2003년 EAFE(European Association of Fisheries Economists) XV Conference에서 발표된 논문을 수정한 것임.

I. INTRODUCTION

The concept of sustainable yield has long dominated the analysis of renewable resources(Schaefer, 1954; Beverton and Holt, 1957). The best known proxy for sustainability is maximum sustainable yield(MSY), defined as the largest annual catch that can be taken while maintaining resource sustainability. With the rationalization paradigm to overcome the open access dynamics, the strategy of maximum economic yield(MEY), which is the sustainable level of catch that produces the greatest economic profits, has become popular. MSY and MEY represent main reference points for fisheries sustainability and benchmarks for fishery management.

Without precise information on age and growth, the most common alternatives to age-based or length-based fisheries stock assessment techniques are biomass dynamics models, commonly referred to as SP models(e.g. Schaefer, 1954; Schnute, 1977; Walters and Hilborn, 1976; Fox, 1970; Clarke, Yoshimoto and Pooley, 1992; Pella and Tomlinson, 1969). A critical underlying assumption of the SP models is that catch in any one year is a linear function of effort and SP models can be represented by the equilibrium state in which the level of catch is equal to the level of surplus growth. This assumption means that SP models cannot estimate biomass annually.

In order to overcome several limits on SP model, ME model developed by Golan et al.(1996a, 1996b) can also be applied to estimate the yearly fishery stock, MSY, and the maximum sustainable biomass, using non-linear programming.

The objective of this paper is to evaluate and compare a SP model and a ME model, using a time-series of data for catch and effort of anchovy, which is one of a major species occupying 7% in the total fisheries landings of Korea. Since the recruitment of anchovy is much more uncertain than the abundance of the adult stages, the stock assessments are also more uncertain. Furthermore, no TAC(Total Allowable Catch) or adaptive management is in place, so the administrations do not require monitoring in order to manage the fisheries. Jacobson et al.(2001) argue that it is difficult to apply existing age-based or length-based fisheries stock assessment techniques to stock assessment of small pelagic fishes such as anchovy and sardine because several characteristics - recruitment variability, rapid somatic growth, and high mortality rates- of small pelagic fishes make their age-structured analysis difficult. Even though current biomass of anchovy can be estimated by using acoustic surveys and trawl surveys(Choi et al., 2001; Bailey and Simmonds, 1990), it is impossible to estimate the yearly fishery stock and parameters. Such things are the most important reasons to conduct fisheries stock assessment of anchovy using indirect methods.

This paper presents SP models and ME model for anchovy stock assessment after a brief summary of fishing types of anchovy and time series data for catch and effort. The remaining part of the paper summarizes the results of two models and their implications for anchovy fisheries.

Ⅱ. DATA FOR ANCHOVY FISHERIES

1. Fishing activity of anchovy

Anchovies are small silvery fishes with blue-green backs. They live up to two or three years, usually never grow larger than 20 cm (8 in), and spawn in the late spring to autumn. Anchovies prefer warmer waters (optimal water temperature: 13 ~ 23$^{\circ}C$) around the world where they swim in massive schools. In Korea they are distributed in all coastal seas as a representative migratory fish species, and primarily feed on planktonic crustaceans and fish larvae.

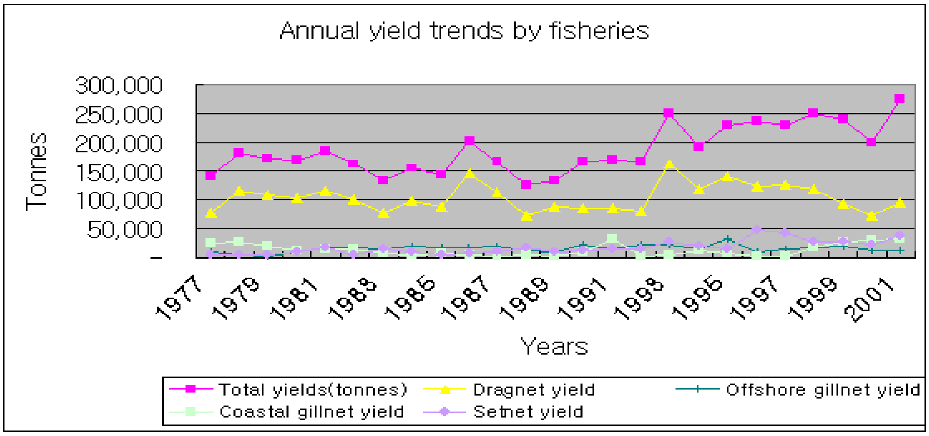
Major fishing gears used in anchovy fishery in Korea are anchovy dragnet, gillnet and set-nets fisheries. Anchovy dragnet accounts for the majority of anchovy harvest in Korea, most of which is processed into the dried. Its offshore and coastal gillnet fishery involves larger anchovies than those of dragnet fishery, and they are used for the pickled or salted. Its set-net fishery yields good quality of the anchovy, catching Spanish mackerel, common mackerel, horse mackerel, hairtail, squid, and so on together.

2. Catch and effort data

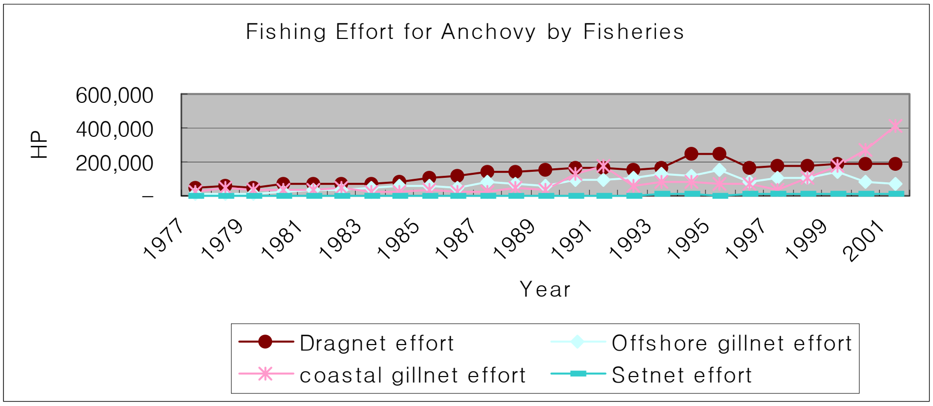
Fishing effort is a key variable in fisheries stock assessment. SP models and ME model assume that the level of catch is a function of effort and biomass, $C_t = qX_tE_t$, where Ct represents the level of catch at t year, q the catchability coefficient, Xt the level of biomass at t year, and Et the level of fishing effort at t year. Total fishing effort has to be expressed in standardized units to account for differences in size and type of vessels and fishing gears. In many cases, however, complete information on all the factors that make up 'effort' is non-exist. For some factors, such as skill, an objective measure is not readily observable. Unfortunately most observable measures of effort, such as days fished, are highly unreliable. As a result, models that do not standardize effort could result in erroneous results. Standardizing effort over time, however, is a complicated task. Most fisheries models also assume that effort is randomly distributed across a fishery, and that catch per unit of effort(CPUE) is proportional to the biomass(Pascoe, 1998).

Some examples of effort proxies in fisheries analysis include: days fished; hours trawled; days*boatsize; days*engine size; day*boat size*engine size; hours trawled*net headrope length; days*crew size; total pot lifts; km nets*hours soaked*lifts, all of which depends on the type of fisheries. Engine size(horsepower) for anchovy is used in this analysis.

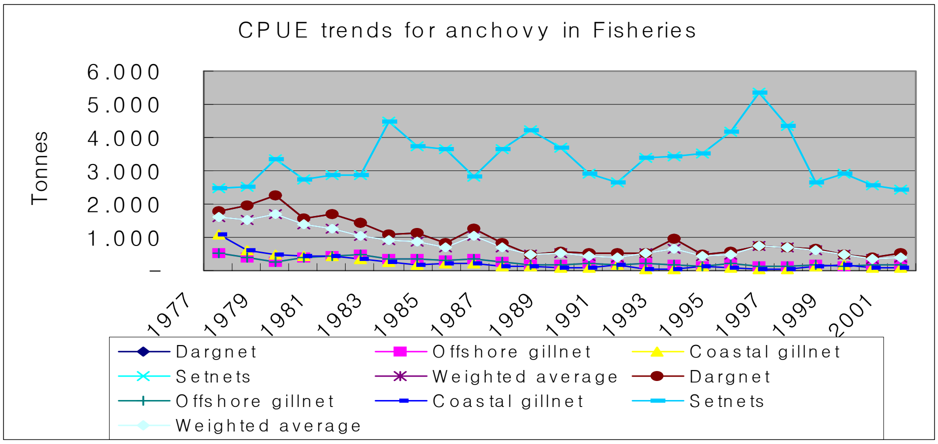
Catch, effort and CPUE data each fishing gear for 25 years (1977 ~ 2001) are presented in in Figure 1, 2 and 3, respectively(Pyo and Lee, 2003). Total anchovy catches have been steadily increasing along with increased effort, showing the range of 130 thousands tonnes to 270 thousands tonnes. The major fishing gear for anchovy is dragnet fishery, while the set net produces the highest CPUE.



[Figure 1] Annual yield trends by anchovy fisheries



[Figure 2] Fishing effort for anchovy fisheries



[Figure 3] CPUE trends for anchovy fisheries

Ⅲ. MODELS FOR FISHERIES STOCK ASSESSMENT

The general purpose of fisheries management is to ensure that the resource is sustainably exploited in optimal fashion over time. A traditional stock assessment is aimed at estimating stock size and statistical information. An important role of stock assessment is to identify whether catch and effort statistics give a good indicator of stock trends. Further, a cost-effective stock assessment for fisheries contributes to compile integrated environmental and economic accounting for fisheries. In this section, traditional SP models and a ME model are focused.

1. SP models

Five different SP models are assessed for their applicability to anchovy species; (1) three logistic growth models, namely the Schaefer (1957) model, the Schnute (1977) model and the Walters and Hilborn (1976) model modifying the Schaefer model; (2) two exponential growth models, namely the Fox (1970) model, and Clarke, Yoshimoto and Pooley (1992) modifying the Fox model.[3] The distinct difference between two groups of models is that growth function (G) of logistic models is symmetrical or parabolic while exponential models adopt asymmetrical growth function, based on the Gompertz curve. Both are composed of the intrinsic growth rate of stock (r), biomass (X) and environmental carrying capacity (K), which is the maximum stock level or virgin biomass, as follows:

For logistic growth models: G = rX(1-X/K);

For exponential growth models: G = rXln(K/X)

From the basic catch and effort data, CPUE or its approximation and the associated level of effort are then computed. Two models of Schaefer and Fox use the finite difference approximation $dU/dt \approx (\overline{U}_{t+1} - \overline{U}_{t-1})/2$, where $\overline{U}_t$ is the average CPUE for a given year:

Schaefer:

$$(\overline{U}_{t+1} - \overline{U}_{t-1})/(2\overline{U}_t) = r - (r/(qk))(\overline{U}_t) - q(\overline{E}_t),$$

Fox:

$$(\overline{U}_{t+1} - \overline{U}_{t-1})/(2\overline{U}_t) = (r - \ln(qk)) - r\ln(\overline{U}_t) - q(\overline{E}_t),$$

where $\overline{E}_t$ is the total effort expended in year t. The parameters r, q, k are estimated by a Pearson or Ordinary Least Squares (OLS) regression analysis with a time series of catch and effort data. Many bio-economic studies incorporate biological parameters estimated by the Schaefer and Fox models. Schnute (1977) argues that a major problem with the Schaefer and Fox models is that they can predict next year's CPUE without specifying next year's anticipated effort, contradicting almost all theory on fisheries biology. Another problem involves the finite difference approximation, which assumes that CPUE is linear over the course of a given year (Clarke et al., 1992).

Schnute (1977) develops a modified version of the Schaefer model using an integration procedure:

3) Hereafter Walters and Hilborn model is referred to as W&H model, and Clarke, Yoshimoto and Pooley model as CYP model.

Schnute:

$$\ln(\bar{U}_{t+1}/\bar{U}_t) = r - (r/(qk))(\bar{U}_t + \bar{U}_{t+1})/2 - q(\bar{E}_t + \bar{E}_{t+1})/2$$

CYP (1992) develop a model which follows Schnute's lead and applies a similar approach to the Fox model, using a Taylor approximation :

$$CY\&P: \ln(\bar{U}_{t+1}) = (2r/(2+r))\ln(qk) + ((2-r)/(2+r))\ln(\bar{U}_t) - (q/(2+r))(\bar{E}_t + \bar{E}_{t+1}).$$

Walters and Hilborn (1976) developed the difference equation method which is relatively more simple than the Schnute model:

Walters and Hilborn:

$$\frac{\bar{U}_{t+1}}{\bar{U}_t} - 1 = r - (r/(qk))(\bar{U}_t) - q\bar{E}_t.$$

Since these are only estimates, regression analysis also tells us how close or far they are from the actual figures. Testing different models was thus aimed at determining which one provides "best" estimates for more accurate management decisions to be made.

2. ME model

1) Formulation of the ME model[4)]

Under conventional estimation rules, we are faced with difficult dynamic problems: (i) an ill-posed problem that the number of parameters to be estimated exceeds the number of observations; and (ii) an underdetermined or underidentified problem which cannot be alleviated by obtaining more data.[5)]

With probabilities p_i such that $\sum_i p_i$ for random variables, x_i, Shannon (1948) defined the entropy as a measure of uncertainty in the distribution of probabilities that maximizes

$$H(p) = -\sum_i p_i \ln p_i = -p \ln p \qquad (1)$$

subject to data consistency (available evidence-data points) in the form of J moment conditions

$$\sum_i p_i x_{ij} = a_{ij}, \quad j = 1, 2, \ldots, J, \qquad (2)$$

and normalization-additivity (adding-up) constraint

$$\sum_i p_i = 1, \qquad (3)$$

where J<N. Consequently, ME model seeks to make the best predictions possible from the limited data information that we have, transforming the evidence-data-empirical moments into the probability distribution representing our state of knowledge (Golan et al. 1996b).

2) ME model for stock assessment of anchovy

For a ME model of fish stock assessment, fisheries production function can be formularized using a Cobb-Douglas production and logistic growth function as follows:[6)]

4) The concept of ME model refers to Golan et al. (1996a) and Golan et al. (1996b). Brierly et al.(2003) applied a Bayesian maximum entropy method to infer stock density and map stock distribution from acoustic line-transect data, but it quite differs from the ME model of Golan et al. (1996a) and Golan et al. (1996b).

5) Chow (1981) and Fulton and Karp (1989) note the general identification problem, but they are based on assumptions to impose arbitrary zero restrictions in order to get identification.

6) Fisheries production function can be combined into Coppola (1995) form and can include exponential growth assumption instead of logistic growth assumption.

$$C_t = A(\prod_{i=1}^{n} E_{it}^{\alpha_i})\, X_t^{\beta}\, \exp(\varepsilon_t) \quad (4)$$

$$X_{t+1} = [X_t + rX_t(1 - \frac{X_t}{K}) - C_t]exp(\mu_t) \quad (5)$$

where i is a vector of fishing gear(in the paper, four methods such as dragnet, offshore gillnet, coastal gillnet, and set nets), α and β are parameters representing the effort and stock elasticity respectively, and ε_t and μ_t are error terms for C and X at time t, respectively. The above functions can be converted to log form as follows:

$$\ln C_t = \ln A + \alpha_1 \ln E_{1t} + \alpha_2 \ln E_{2t} + \ldots\ldots + \alpha_n \ln E_{nt} + \beta \ln X_t + \varepsilon_t \quad (4')$$

$$\ln X_{t+1} = \ln X_t + \ln S_t + \mu_t \quad (5')$$

where $S_t = 1 + r(1 - \frac{X_t}{K}) - \frac{C_t}{X_t}$.

In this formulation the observable variables are C_t and E and the parameters to be internally derived from the formulation are the probability distributions of A, α_i, β, r, X_t, K, ε_t and μ_t. Therefore, the above formulations are involved in an ill-posed problem as they have much more parameters estimated than observed variables. In addition, there is a method to impose prior restrictions on the parameter estimates by spanning the possible parameter range for each parameter. For example, if A, α_i and β are believed that they range between 0 and 1, they will be specified by a tri-uniform distribution such as [0, 0.5, 1].

$$A = p_1^A \cdot 0 + p_2^A \cdot 0.5 + p_3^A \cdot 1 \quad (6)$$

$$\alpha_i = p_1^{\alpha_i} \cdot 0 + p_2^{\alpha_i} \cdot 0.5 + p_3^{\alpha_i} \cdot 1 \quad (7)$$

$$\beta = p_1^{\beta} \cdot 0 + p_2^{\beta} \cdot 0.5 + p_3^{\beta} \cdot 1 \quad (8)$$

In such context, limited prior information for r and K can be imposed by using the estimates from SP model as follows:

$$r = p_1^r \cdot 0 + p_2^r \cdot \frac{m}{2} + p_3^r \cdot m \quad (9)$$

$$K = p_1^K \cdot 0 + p_2^K \cdot \frac{n}{2} + p_3^K \cdot n \quad (10)$$

$$X_t = p_{t1}^X \cdot 0 + p_{t2}^X \cdot \frac{h}{2} + p_{t3}^X \cdot h \quad (11)$$

$$\varepsilon_t = p_{t1}^{\varepsilon} \cdot (-e) + p_{t2}^{\varepsilon} \cdot 0 + p_{t3}^{\varepsilon} \cdot (+e) \quad (12)$$

$$\mu_t = p_{t1}^{\mu} \cdot (-e) + p_{t2}^{\mu} \cdot 0 + p_{t3}^{\mu} \cdot (+e) \quad (13)$$

where m, n and h stand for upper bounds of r, K and X_t respectively, and e is specified to be symmetric around zero for ε_t and μ_t

In conclusion, the generalized stochastic non-linear ME model for stock assessment of anchovy in the Korean coastal seas can be structured in scalar-summation notation, using a criterion with nonnegative probability factors, as

$$Max[-\sum_g \sum_j p_j^g \ln p_j^g - \sum_l \sum_t \sum_j p_{tj}^l \ln p_{tj}^l] \quad (14)$$

subject to the data consistency with (4)′, (5)′, (6), (7), (8), (9), (10), (11), (12), (13) in which m, n, h and e are replaced by 2, 1000000, 500000 and 0.3, respectively, and the adding-up constraints:

$$\sum_j^3 p_j^g = 1,\ \sum_j^3 p_{tj}^X = 1,\ \sum_j^3 p_{tj}^{\varepsilon} = 1,\ \sum_j^3 p_{tj}^{\mu} = 1 \quad (15)$$

where

$g = A, \alpha, \beta, r, K$ and $l = X, \varepsilon, \mu$, and $t = 1,2,3,\ldots,n-1$.

This formulation is a general non-linear inversion procedure for recovering both time-invariant and time-variant parameters. These estimates may be also used as a basis for defining measures of uncertainty and precision for fish stock assessment (Golan et al. 1996a).

Ⅳ. RESULTS

1. SP models

For MSY of the anchovy fisheries, the Schaefer, Schnute, Walters&Hilborn, Fox, and CYP production models were estimated using OLS as shown in Table1. Surprisingly all models except the CYP model did not fit the data well: low R-square, and insignificant t-statistics for all fisheries. The CYP model has coefficients with the proper signs and t-statistics significant at the 10% level.7) Due to the poor performance of all the models except CYP model, the subsequent analysis focuses on the CYP model only. Such a result demonstrates the importance of choosing appropriate models for the case under investigation.

Parameters- r, q, K, and MSY were estimated in Table 2. The catch (273,927 tons) in 2001 exceeded the MSY (198,364 tons), which means

<Table 1> Results of estimated parameters and statistic in SP models

Models	Independent Variables	Parameters	Adjusted r^2	t-statistic	D-W statistic	Multicollearity
Schaefer	Constant Totalhp CPUEhp	-0.08345 0.2599 -2.0E-08	-0.11	-0.334 0.313 -0.012	1.789	Tolerance 0.379 VIF 2.641
Fox	Constant Ln(U) totalhp	-0.0124 -9.391E-4 -3.3E-7	-0.12	-0.058 -0.005 -0.192	1.808	Tolerance 0.204 VIF 4.897
Schnute	Constant (E+E1)/2 (U+U1)/2	-0.0292 -1.7E-7 4.412E-3	-0.12	-0.097 -0.117 0.043	2.112	Tolerance 0.303 VIF 3.301
Walters & Hilborn	Constant Totalhp CPUEhp	0.3027 -0.1053 -1.31E-6	-0.064	1.160 -1.169 -1.006	2.005	Tolerance 0.986 VIF 1.014
CYP	Constant E+E1 Ln(U)	0.141 -5.882E-7 0.530	0.818	2.922*** -3.164*** 2.196**	1.904	Tolerance 0.250 VIF 3.996

Note: *** stands for significant level of 1%, and ** 5% level.

<Table 2> Results of estimated parameters in CYP model

r	q	K	E(MSY)	C(MSY)	X(MSY)
0.61425	1.537E-6	877,684	399,648	198,364	322,881

<Table 3> Results of estimated parameters in the ME model

A	α_1	α_2	α_3	α_4	β	r	K
0.505	0.095	0.0433	0.059	0.034	0.803	0.658	1,302,000

the current level of catch for anchovy are seriously overexploited. In this case, the actual level of effort has substantially exceeded that which produces MSY, so it is possible to assume that biomass is at a lower level than it may be in the long run, and that the lower biomass would result in a lower level of catch.

2. ME model

In this analysis, the GAMS(General Algebraic Modeling System; Brooke et al., 1998) program is used to solve the numerical optimization problems using non-linear programming. Parameters- A, α, β, r, K -are estimated in Table 3. Intrinsic growth rate (r) in the ME model is similar to that of the CYP model, while environmental carrying capacity (K) in this model is quite greater than that of the CYP model. Taking into account anchovy's life span (1~2 years), the intrinsic growth rates of 0.61 and 0.62 estimated in the CYP model and ME model are likely to be reasonable.

In terms of using the estimates of parameters as shown in Table 3, the estimated equations are constructed as follows:

$$C_t = 0.505 E_{1t}^{0.095} E_{2t}^{0.001} E_{3t}^{0.059} E_{4t}^{0.034} X_t^{0.803} \quad (16)$$

$$X_{t+1} - X_t = 0.658 X_t \left(1 - \frac{X_t}{1{,}302{,}000}\right) - C_t \quad (17)$$

From the results in the equation (16), the anchovy fishery demonstrates decreasing returns to effort and stock. The effort elasticity of catch for anchovy dragnet, offshore gillnet, coastal gillnet, and set nets are 0.095, 0.001, 0.059, and 0.034, respectively. The elasticity for dragnets is highest, which means that a 10 percent increase in effort for dragnets would increase catch of anchovy by only 0.95 percent. On the contrary, a 10 percent decrease in effort for set nets would only decrease anchovy catch by 0.95 percent. In addition, the stock elasticity is about 0.803.

<Table 4> Estimated annual stock of anchovy in coastal seas of Korea

Years	Estimated probabilities			Estimated stock
	X_t=0	X_t=500,000	X_t=1,000,000	
1977	0.14	0.33	0.53	695,000
1978	0.164	0.33	0.506	671,000
1979	0.221	0.33	0.449	614,000
1980	0.261	0.33	0.409	574,000
1981	0.132	0.33	0.538	703,000
1982	0.195	0.33	0.475	640,000
1983	0.23	0.33	0.44	605,000
1984	0.234	0.33	0.436	601,000
1985	0.172	0.33	0.498	663,000
1986	0.193	0.33	0.477	642,000
1987	0.33	0.196	0.474	572,000
1988	0.307	0.33	0.363	528000
1989	0.303	0.33	0.367	532,000
1990	0.247	0.33	0.423	588,000
1991	0.282	0.33	0.388	553000
1992	0.158	0.33	0.512	677,000
1993	0.111	0.33	0.559	724,000
1994	0.313	-	0.687	687,000
1995	0.291	-	0.709	709,000
1996	0.308	-	0.692	692,000
1997	0.33	-	0.67	670,000
1998	0.33	0.031	0.639	654,500
1999	0.33	0.099	0.571	620500
2000	0.33	0.147	0.523	596500
2001	0.33	0.122	0.548	609000

7) According to CYP(1992), better regression fits are expected from the CYP model since its functional form is more straightforward than those of any other SP models.

From the logistic growth function of equation (17) estimated using ME model, the MSY is calculated to be 213,287 tons, which is slightly higher than that of CYP model (198,364 tonnes). The biomass for MSY is 651,000 tons, which is considerably greater than that of the CYP model (322,881 tons). In the annual results of the estimated stock of Table 4, it is found that the annual biomass estimated in the ME model had declined for several years, and then recovered the year after that, which is around the level of the maximum sustainable biomass estimated.

V. SUMMARY AND CONCLUSIONS

As a contribution to developing fishery stock assessment method and optimum sustainable yield, SP model and ME model are employed for anchovy in this paper.

For selecting the appropriate models of five traditional surplus models - Schaefer, Schnute, Walters and Hilborn, Fox, and CYP models are tested in effort and catch data of anchovy fisheries. Surprisingly all the models except CYP model fail to satisfy statistical standards such as fitness and significance. Generally, the CYP model holds good fitness and statistically significant level for anchovy fisheries.

Taking account of the full range of uncertainties into non-linear programming, ME model can also be applied to estimate the yearly fishery stock, MSY, and the maximum sustainable biomass. The observed variables in the model are catch and effort data while unknown parameters are probability distribution of constant, intrinsic growth rate, environmental carrying capacity, biomass, α and β(a sort of elasticity for effort and biomass). ME formulation seeks a solution that maximizes the distribution of probabilities reflecting our uncertainty about parameters subject to data consistency and normalization-additivity requirements. The ME approach offers a method of recovering the desired parameters of stock assessment with a minimal amount of prior information when the state system is nonlinear and the state observation is noisy.

Intrinsic growth rate (r) in ME model is similar to that of CYP model, while environmental carrying capacity (K) in this model is quite greater than that of CYP model. Taking into account anchovy's life span (1~2 years), the intrinsic growth rates of 0.61 and 0.658 estimated in the CYP model and the ME model are likely to be reasonable. The MSY in the ME model is calculated to be 213,287 tons which is slightly higher than that of the CYP model (198,364 tons)[8], while the biomass for MSY is 651,000 tons which is considerably greater than that of CYP model (322,881 tons). The annual biomass estimated in ME model had declined for several years, and then recovered the year after that, which is

8) NFRDI(2004) estimated anchovy's MSY and its optimal sustainable yield to be 117,417 tons and 224,667 tons, using Fox model and ABC(Allowable Biological Catch) model, respectively,

around the level of the maximum sustainable biomass estimated.

This paper can be extended to estimate maximum economic yield considering price and cost, and to employ alternative growth function and production function. In addition, economic factors and fishing efforts such as price, cost, technical change and a reasonable function of fishing inputs should simultaneously be considered.

REFERENCES

Bailey, R.S. · Simmonds, E.J. "The use of acoustic surveys in the assessment of the North Sea herring stock and comparison with other methods" Reun. Conns. int Explor. Mer., 189: 9~17, 1990.

Beverton, R.J.H. · S.J. Holt "On the Dynamics of Exploited Fish Populations" Fisheries Investment Series 2, Vol. 19, UK Ministry of Agriculture and Fisheries, London, 1957.

Brierley, A.S. · Gull, S.F., Wafg, M.H. "A Baysian maximum entropy reconstruction of stock distribution and inference of stock density from line-transect acoustic-survey data", ICES J. Marine Science, 60: 446~452, 2003.

Brooke, A. · D. Kendrick · A. Meeraus · R. Raman "GAMS A User's Guide" GAMS Development Corporation, 1998.

Choi, S,K · Kim, J.Y. · Kim, S.S. · Choi, Y. M. · Choi, K.H. "Biomass estimation of anchovy by acoustic and trawl surveys during spring season in the southern Korean waters" J. Korean Soc. Fish. Res., 4: 20~29, 2001.(in Korean)

Chow, G. "Econometric Analysis by Control Methods", John, Wiley & Sons, 1981.

Clarke, R.P. · S.S. Yoshimoto · S.G. Pooley "A Bioeconomic Analysis of the North-western Hawaiian Islands Lobster Fishery" Marine Resource Economics 7: 115~140, 1992.

Coppola, G. "A Production Function for Fisheries: an Analytical Approach" Paper presented at the 5th Bioeconomic Modelling Workshop, Edinburgh, pp.24~27 October 1995.

Fox, W.J. "An Exponential Surplus Yield Model for Optimising Exploited Fish Populations" Transactions of the American Fisheries Society 99: 80~88, 1970.

Fulton · Karp, L. "Estimating the Objectives of a Public Firm in a Natural Resources Industry" Journal of Environmental Economics and Management 16: 268~287, 1989.

Golan, A. · G. Judge · L. Karp "A Maximum Entropy Approach to Estimation and Inference in Dynamic models or Counting Fish in the Sea using Maximum Entropy" Journal of Economic Dynamics and Control 20: 559~582, 1996a.

Golan, A. · G. Judge · D. Miller "A Maximum Entropy Econometrics" John Wiley & Sons, 1996b.

Jacobson, L.D. · De Oliveira, J.A.A. · Barange, M. · Cisneros-Mata, M.A. · Felix-Uraga, R. · Kim, J.Y. · Natsuura, Y. · Niquen, M. · Porteiro, C. · Rothschild, B. · Sanchez, R. P. · Serra, R. · Uriarte, A. · Wada, T. "Surplus production, variability, and climate change in the great sardine and anchovy fisheries" Can. J. Fish. Aquat. Sci., 58:1891-1903, 2001.

NFRDI(National Fisheries Research and Development Institute) "Report on stock assessment of target species of TAC", 2005.(in Korean)

Pascoe, S. "A Bioeconomic Analysis of the UK Fisheries of the English Channel" PhD Thesis, University of Portsmouth, UK, 1998.

Paris, Q.・R.E. Howitt "An Analysis of Ill-posed Production Problems using ME" American Journal of Agricultural Economics 80: 124~138, 1998.

Pella, J.J.・P.K. Tomlinson "A Generalized Stock Production Model" Bulletin of the Inter-American Tropical Tuna Commission 13: 419~496, 1969.

Pyo, H.D.・K.N. Lee "A Comparative Analysis of Surplus Production Model and Maximum Entropy Model for Estimating the Anchovy's Stock" Session 12:Fisheries Dynamics(1), pp.2~8 in: Proceedings of EAFE(European Association of Fisheries Economists) XV Conference, IFREMER, Brest, France, pp.15~16 May 2003.

Schaefer, M.B. "Some Aspects of the Dynamics of Populations Important to the Management of Commercial Marine Fisheries" Bulletin of the Inter-American Tropical Tuna Commission 1:247~285, 1954.

Schaefer, M.B. "A Study of the Dynamics of the Fishery for Yellowfin Tuna in the Eastern Tropical Pacific Ocean" Bulletin of the Inter-American Tropical Tuna Commission 2: 247~285, 1957.

Schnute, J. "Improved Estimates from the Schaefer Production Model: Theoretical Considerations" J. the Fisheries Research Board of Canada 34: .583~603, 1977.

Shannon, C.E. "A Mathematical Theory of Communication" Bell System Technical Journal 27: 379~423, 1948.

Walters, C.J.・R. Hilborn "Adaptive Control of Fishing System" J. Fisheries Research Board of Canada 33: 145~159, 1976.