Bioeconomic Modeling for the Evaluation of Fishery Resources Based on the Schaefer Model

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ABSTRACT

In this study, we tried to develop a theoretical framework based on the Schaefer model and establish bioeconometric models to estimate the index of fishery resources using cross-country macro data. The characteristics of our model are that we consider the effect of natural fluctuations of fishery resources over time (in other words, we assume not a steady-state equilibrium, but a state of disequilibrium) and differences in country. Our model indicated that Schaefer model, which has been applied to assess fishery resources in local fishery, can fit comfortably to the macro data in OECD countries. Our model need only an essential socioeconomic data in fishery and has a potential to supplement information on the status of resources in non-OECD or developing countries where scientific surveys are costly or may not be a workable option.

INTRODUCTION

In the field of resource economics, there exists a famous theoretical model, namely, the Schaefer model. This model enables us to capture the mechanisms of resource fluctuations by using only essential variables. Therefore, it has been applied to assess many types of fish stocks in local fisheries (e.g. see Haddon, 2011, p. 299-300, for Eastern Pacific yellowfin tuna, Tanaka, 2012, p. 65, for Hippoglossus stenolepis at the west coast in the North American continent).

In the past, the model has not been applied for cross-country macro (or multi species aggregate) data because the theory aims to capture the resource fluctuation of specific specie in local area. However, Tanaka (2001, p. 133) sharply indicated that the fish catch of individual specie changes on a grand scale, but that of total species tends to balance. This suggests that there is a carrying capacity for aggregate fish stock and it is mutually related to species alternation. Therefore, we could indicate a possibility that, in global scale, the fluctuation of aggregate fish stock is explained by total effort for aggregate fish catch.

In this study, we first developed a theoretical framework based on the Schaefer model and established econometric models to estimate the quantity of fishery resources, under the assumption that fish biomass is not stable and catchability coefficient is different in each country. Second, we applied the econometric models to data from the OECD fisheries and simulated fish biomass. The result proved the Schaefer model is valid, even if the data used are somewhat rough, like cross-country aggregate data.

BIOECONOMIC MODELING

According to the Schaefer model (Schaefer, 1957), in the bioeconomic analysis of fisheries, the growth of fish biomass and the short-term catch function can be shown, respectively, as follows:

$$\frac{dP}{dt} = KP_t(L - P_t) - Y_t, \tag{1}$$

$$Y_t = qX_t P_t, \tag{2}$$

where, P_t is the fish biomass in time t; K (= r/L) is the intrinsic growth rate of fish stock r over the carrying capacity of the environment L; Y_t is the fish catch in time t; q is the catchability coefficient, defined as the fraction of the biomass fished by an effort unit; and X_t is the fishing effort.

If the fish biomass P_t is not at equilibrium, i.e., if $dP/dt \neq 0$, then the left-hand side of equation (1) will not be equal to zero; this can be described as follows:

$$\frac{dP}{dt} = \Delta P = P_{t+1} - P_t. \tag{3}$$

By substituting equation (3) into equation (1), we obtain equation (4) as follows:

$$P_t - P_{t-1} = KLP_{t-1} - KP_{t-1}^2 - Y_{t-1}. \tag{4}$$

Dividing both sides of equation (4) by P_{t-1}, we get the next equation:

$$\frac{P_t - P_{t-1}}{P_{t-1}} = KL - KP_{t-1} - \frac{Y_{t-1}}{P_{t-1}}. \tag{5}$$

Then, substituting equation (2) into equation (5), we obtain equation (6) as follows:

$$\frac{Y_t X_{t-1} - Y_{t-1} X_t}{Y_{t-1} X_t} = KL - \frac{K}{q} \cdot \frac{Y_{t-1}}{X_{t-1}} - qX_{t-1}. \tag{6}$$

Through modification, equation (6) can be rewritten as follows:

$$Y_t = (1 + KL)\frac{X_t Y_{t-1}}{X_{t-1}} - K\frac{1}{q}\frac{X_t Y_{t-1}^2}{X_{t-1}^2} - qX_t Y_{t-1}. \tag{7}$$

We replaced (1+KL) by α, - K/q by β, and - q by γ, and obtained ***<u>estimation model I</u>*** as follows:

$$Y_t = \alpha \frac{X_t Y_{t-1}}{X_{t-1}} + \beta \frac{X_t Y_{t-1}^2}{X_{t-1}^2} + \gamma \; X_t Y_{t-1}, \tag{8}$$

where the sign of parameter α is positive and $\alpha \geq 1$ (because α = (1+ KL) and $KL \geq 1$), and the signs of β and γ are definitely negative.

Next, we assume that the data are panel data composed of yearly time series and country cross-section, and that the catchability coefficient q is different for each country i. Then, equation (7) can be rewritten as follows:

$$Y_t = (1+KL)\frac{X_t Y_{t-1}}{X_{t-1}} - K\frac{1}{q_i}\frac{X_t Y_{t-1}^2}{X_{t-1}^2} - q_i X_t Y_{t-1}. \qquad (9)$$

We again replace (1+KL) by α, - K/q_i by β_i, and - q_i by γ_i to obtain equation (10):

$$Y_t = \alpha\frac{X_t Y_{t-1}}{X_{t-1}} + \beta_i\frac{X_t Y_{t-1}^2}{X_{t-1}^2} + \gamma_i X_t Y_{t-1}. \qquad (10)$$

Definitely, β_i and β_j equal to -K/q_i and -K/q_j, respectively; therefore, β_j can be substituted by β_i, as follows:

$$\beta_j = \frac{-K/q_j}{-K/q_i}\beta_i = (\frac{q_j}{q_i})^{-1}\beta_i = (1+\frac{q_j - q_i}{q_i})^{-1}\beta_i = (1+d_j)^{-1}\beta_i, \qquad (11)$$

where, d_j is $(q_j - q_i)/q_i$.

Similarly, γ_i and γ_j equal to -q_i, and -q_j, respectively; therefore, γ_j can be substituted by γ_i, as follows:

$$\gamma_j = \frac{-q_j}{-q_i}\gamma_i = (\frac{q_j}{q_i})\gamma_i = (1+\frac{q_j - q_i}{q_i})\gamma_i = (1+d_j)\gamma_i. \qquad (12)$$

By substituting equation (11) and (12) into (10), we get

$$Y_t = \alpha\frac{X_t Y_{t-1}}{X_{t-1}} + \beta_i(1+d_j)^{-1}\frac{X_t Y_{t-1}^2}{X_{t-1}^2} + \gamma_i(1+d_j)X_t Y_{t-1}. \qquad (13)$$

Therefore, we obtain ***estimation model II*** (which enables us to estimate the effects of each country's catchability coefficient) by using a dummy variable as follows:

$$Y_t = \alpha\frac{X_t Y_{t-1}}{X_{t-1}} + \beta_i(1+\sum d_j \cdot dummy_j)^{-1}\frac{X_t Y_{t-1}^2}{X_{t-1}^2} + \gamma_i(1+\sum d_j \cdot dummy_j)X_t Y_{t-1}, \qquad (14)$$

where the sign of parameter α is positive and $\alpha \geq 1$(because α = (1+ KL) and $KL \geq 1$), and the signs of β_i $(1+\sum d_j dummy_j)^{-1}$ $\forall j$ and γ_i $(1+\sum d_j dummy_j)$ $\forall j$ are negative.

By applying ***estimation model I*** [equation (8)] or ***estimation model II*** [equation (14)] to the fish catch (Y) and fishing effort (X) data, we can estimate the value of parameter γ or γ_i and d_j. This means that we can calculate q or q_j, because q = -γ and q_j = -γ_i (1+d_j).

Since Y_t, X_t, and q (or q_j) are given, we can catch the fluctuation of the fish biomass P_t (or $P_{t,j}$) from equation (2) as follows:

$$P_{t(j)} = \frac{Y_{t(j)}}{q_{(j)} X_{t(j)}}. \qquad (15)$$

APPLICATION OF THE MODEL TO OECD FISHERIES

The Estimation Model

We first estimate equations (8) (***estimation model I***) and (14) (***estimation model II***), and then calculate the fish biomass P_t with the estimation results and equation (15).

The Data

To check the feasibility of the model, we used the data of developed countries because of their easy availability. The data were obtained primarily from "Fishstat" (FAO) and "Review of Fisheries in OECD Countries" (OECD). The descriptive statistics of the relevant variables are shown in Table 1. We show fish catch as Y and the root of the multiplication of the number of vessels and the number of labor as X.[1] The data in 22 OECD countries from 1998 to 2007 are available, but they include missing values. As a result, the number of observations is 155.

Table 1 Descriptive statistics

	Fish catch [Y] (1,000 tonnes)	Fishing effort [X] (-)	Vessels [-] (GRT/GT)	Labor [-] (Number)
Average	1007.86	102414.34	273121.26	45567.02
S. D.	1222.58	144995.96	343334.35	72798.12
Min.	20	3104.33	15425	481
Max.	5314.80	654889.83	1548071	277042
No. of Obs.	155	155	155	155
Source	FAO "Fishstat"	$(\text{Vessels x Labor})^{1/2}$	OECD "Review of Fisheries in OECD Countries"	OECD "Review of Fisheries in OECD Countries"

Note 1: [ ] indicates the variable and ( ) the unit used in the table.

Note 2: We supplemented the missing Japanese data from other available sources: The Ministry of Agriculture, Forestry and Fisheries (MAFF) "Survey on Marine Fishery Production"[2] for fish catch; Fisheries Agency "Survey on Vessels in 2006"[3] for vessels; Ministry of Agriculture, and Forestry and Fisheries (MAFF) "Survey of Persons Engaged in Fishery"[4] for labor. However, this supplement had little impact on the estimation results.

Estimation Results

Table 2 shows the estimation results of ***estimation models I*** and ***II***. We used the statistical software TSP version 4.5 for the estimation. The estimation method used for ***estimation model I*** is ordinary least squares (OLS) and that for ***estimation model II*** is non-linear least squares (NLS).

From the results of ***estimation model I,*** which is a more simple form, the estimate of α is positive and $\alpha \geq 1$, estimates of β and γ are negative, and all of them are statistically significant at the 1% level. Thus, the results satisfy the theoretically expected sign conditions. From the perspective of the goodness of fit, R^2 is 0.952 and *adj*. R^2 is 0.951, and the overall fit of the model is sufficiently large. These results suggest that our model can perform well using the cross-country OECD fisheries data.

From the results of ***estimation model II,*** which considers the effect of each country's catchability as the dummy variables, the estimate of α is positive and $\alpha \geq 1$, and the estimates of β and γ are negative. Here, α and γ are statistically significant at the 1% level, but β is not significant at the 10% level (we might need to collect further data to improve the significance of β, because we use each country's dummy variables). The signs were found to be consistent with theoretical rationale. With regard to the dummy variable coefficients, 18 out of 21 are significant and the values are larger than -1; this is desirable from the theoretical sign condition [see, equation (14)]. On the determination coefficient, R^2 is 0.915 and *adj.* R^2 is 0.900, and the indicator of fitness of the model is sufficiently large. On the whole, ***estimation model II*** performs as efficiently as ***estimation model I***.

Table 2 Estimation results

Parameter	*Estimation model I* Estimate		(t-value)	*Estimation model II* Estimate		(t-value)
α	1.21	***	(25.16)	1.74	***	(14.82)
β	-6.75	***	(-8.02)	-1.82		(-0.55)
γ	-2.82×10^{-7}	***	(-3.54)	-5.58×10^{-6}	***	(-3.58)
d_1 [Australia]				-0.98	***	(-22.13)
d_2 [Belgium]				-0.99	***	(-17.64)
d_3 [Denmark]				-0.82	***	(-2.71)
d_4 [Finland]				-0.97	***	(-16.16)
d_5 [France]				-0.98	***	(-26.24)
d_6 [Germany]				-0.96	***	(-13.82)
d_7 [Greece]				1.46		(0.64)
d_8 [Ireland]				-0.97	***	(-18.88)
d_9 [Italy]				0.30		(0.62)
d_{10} [Netherlands]				-0.97	***	(-16.33)
d_{11} [Poland]				-0.98	***	(-27.47)
d_{12} [Portugal]				-0.99	***	(-61.99)
d_{13} [Spain]				-0.14		(-0.59)
d_{14} [Sweden]				-0.93	***	(-7.69)
d_{15} [United Kingdom]				-0.97	***	(-17.76)
d_{16} [Iceland]				-0.86	***	(-3.46)
d_{17} [Japan]				-0.98	***	(-23.46)
d_{18} [Korea, Rep.]				-0.98	***	(-33.76)
d_{19} [Mexico]				-0.59	***	(-5.41)
d_{20} [New Zealand]				-0.92	***	(-7.12)
d_{21} [Norway]				-0.91	***	(-5.55)
R^2	0.952			0.915		
Adj. R^2	0.951			0.900		
Number of observation	155			155		
Method	Ordinary least squares (OLS)			Nonlinear least squares (NLS)		

Note 1: *p < 0.10, **p < 0.05, ***p < 0.01.

Note 2: The benchmark of d_j (j = 1, …, 21) is Turkey.

Note 3: The values of R^2 are calculated as the square of correlation coefficient between the observation value and the estimation value of fish catch (Y). The values of *adj.* R^2 are calculated as $1-(1-R^2)*(n-1)/(n-k)$, where n is the number of observations and k is the number of independent variables. On how to calculate R^2, see Minotani and Maki (2010, p. 205).

Simulation of fish biomass

Figure 1 shows the simulation results of fish biomass (*P*) based on the results of ***estimation models I*** and ***II***. Both simulation results show similar fluctuations, and the fish biomass of commercial fish in the OECD countries tends to increase from 1999 to 2002, decrease from 2002 to 2004, and increase again from 2004 to 2007. The scale of fish biomass is about 40 to 80 times as large as the scale of fish catch.

Additionally, there seems to be a positive relation between fish biomass and fish catch. This supports equation (2) in the Gordon-Schaefer model, which states that the more the fish biomass, the more the fish catch. In this analysis, since we used macro data of OECD countries, there is the possibility that a large-scale natural factor such as *regime shift* could have affected the fish biomass and thereby the total harvest of OECD countries. [5]

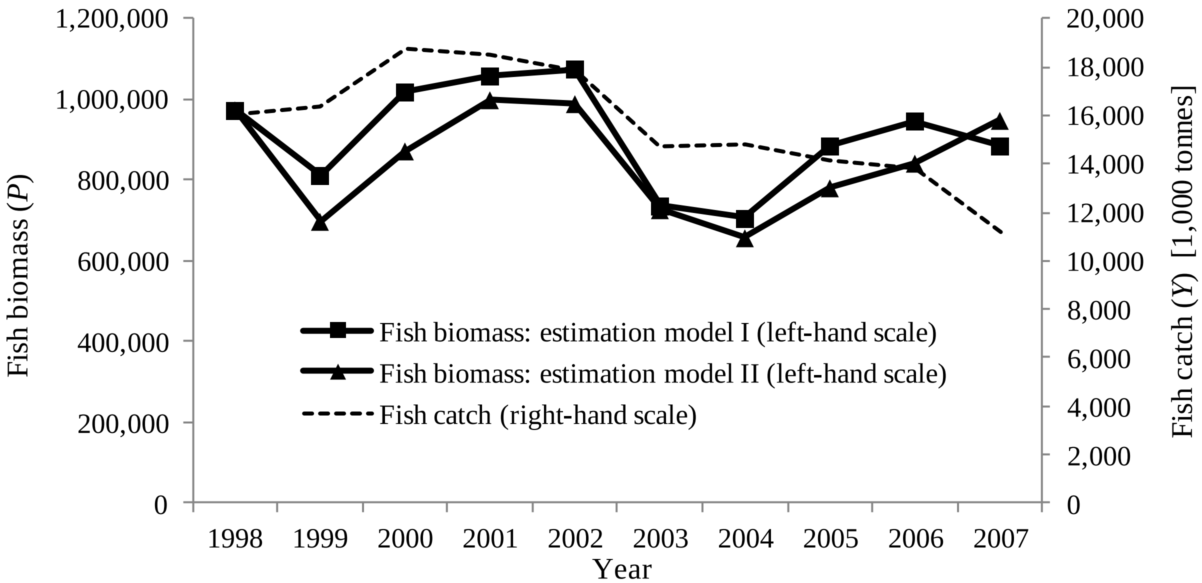

Fig. 1 Simulation results of fish biomass (*P*)

CONCLUSION

In this study, we first developed a theoretical framework based on the Schaefer model and established econometric models to estimate the quantity of fishery resources. Second, we applied the econometric models to data of the OECD fisheries and simulated the index of fish biomass.

The results proved the validity of our models and showed that we can capture the fluctuation of the biomass even if the data used are somewhat rough, like cross-country aggregate data. Our model enables us to simulate the fluctuation of fish biomass by using only fish catch and fishing effort data. Thus, the approach is expected to apply to the fisheries in developing countries or disastered fisheries (e.g., those destroyed by a tsunami) in developed countries where scientific surveys are too expensive and cannot be conducted.

As a future challenge, we need to consider the effect of time trend on the catchability coefficient *q*. In this study, since we used cross-country panel data, we could consider the effect of difference in country on the catchability coefficient *q* by using ***estimation model II***, but we could not consider the effect of time trend.[6] By considering the effect of time trend, we can perform a more elaborate simulation of the fluctuation of fish biomass.

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ENDNOTES

[1] Ariji (2004, p. 112) indicates that fishing effort can be expressed as a multiplication of plural input variables.
[2] URL: http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001061498
[3] URL: http://www.ship-densou.or.jp/kancho/suisan/2008-1gyosen.pdf
[4] URL: http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001061630
[5] For an example of a decrease in Japan’s fishery resources due not to fish catch but to natural factors, see Yagi (2011, p. 26).
[6] For an example of panel data analysis in the field of fishery economics, see Oishi and Tada (2011) and Tada and Oishi (2011).