▸ Article ◂

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Methodology and Application of a Model to Estimate Fishery Resource Trends by Effort and Catch Data

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【abstract】

In this study, we first established a resource economic model to estimate fish biomass using Schaefer's bioeconomic model under the assumption that fish biomass is not at equilibrium. Second, we developed a model capable of estimating country-specific catchability coefficients. Third, we applied OECD fishery data to the model on a trial base. The results indicated that the Schaefer model, which has been applied to assess fishery resources for single species, can comfortably fit the macro data from OECD countries. Next, we simulated annual trends in fish stock levels, called relative biomass, and is defined as the ratio of fish stocks to carrying capacity. Our result showed that from 1998 to 2007, relative biomass stably fluctuated in a large sense. Our model requires only secondary fishery data and has the potential to supplement information on resource statuses in non-OECD developing countries, where original surveys are costly or otherwise not viable options.

【keywords】

Schaefer model, OECD fishery data, relative biomass

1. Introduction

In the field of resource economics, a famous theoretical model called the Schaefer model(1), enables capture of the mechanisms behind resource fluctuations using only essential variables, i.e., fish catches and fishing effort. Therefore, it has been applied to assess many types of fish stocks in local fisheries (e.g., Haddon (2011), pp. 299-300, for Eastern Pacific yellowfin tuna; Tanaka (2012), p.65, for *Hippoglossus stenolepis* on the North American west coast).

In the past, the Schaefer model has not been applied for cross-country macro (or multi-species aggregate) data because the theory aims to capture resource fluctuations of specific species in local areas. However, Tanaka (2001), p.133 indicated that while the fish catch of individual species significantly changes that of total species tends to balance. Introduction in Iwasaki (2009) also indicates that global fish biomass basically remains static because, while some species may be decreasing, others are increasing.

The Schaefer model is a type of surplus production model that pools the overall effects of recruitment, growth, and mortality (all aspects of production) into a single production function (Haddon (2011), p.285). Other examples of such models include the Fox model and the Pella and Tomlinson model (Nose *et al.* (1998), pp.73-82). The Fox model, famous in the demographic research field, postulates that intrinsic growth follows the Gompertz curve. This is in contrast to the Schaefer model, which uses the logistic curve popular in the field of ecological studies (Tanaka (2012), p.55). Pella's and Tomlinson's model is a generalized form of Schaefer's and Fox's models, but it is complex relative to Schaefer's model, especially under the assumption that fish biomass is not at equilibrium. Currently, applying the Pella and Tomlinson model in the estimation is difficult. Taking the above into consideration, we have adopted the Schaefer model(2)(3).

The academic contribution of this paper is threefold. First, we constructed a resource economic model to estimate fish biomass using Schaefer's bioeconomic model, under the assumption that fish biomass is not at equilibrium. Second, we demonstrated that the model can estimate country-specific catchability coefficients (q_i)(4). Third, we indicated that the conventional Schaefer model can be well suited to macro fishery data in OECD countries. Finally, we simulated an index of stock levels, called relative biomass, which represents the ratio of fish stock to carrying capacity (P/K), under the above two scenario (i.e., the conventional constant q model and country specific q_i model), as a trial simulation.

Ideally, a natural scientific approach is necessary to rigorously analyze fish biomass including species alternations. Our models, in constant, need only secondary fishery economic data, which has potential to provide approximate information on the status of resources in countries where original surveys are not readily available.

2. The model

In the Schaefer model, the growth of fish biomass and short-term catch function can be shown, respectively, as follows(5):

$$\frac{dP_{i,t}}{dt} = r\left(1 - \frac{P_{i,t}}{K_i}\right)P_{it} - Y_{i,t} \tag{1}$$

$$Y_{i,t} = qX_{i,t}P_{i,t} \tag{2}$$

where $P_{i,t}$ is the fish biomass in time t in country i; r is the intrinsic fish stock growth rate; K_i is the environment's carrying capacity in country i; $Y_{i,t}$ is the fish catch in time t in country i; q is the catchability coefficient, defined as the fraction of the biomass fished by an effort unit; and $X_{i,t}$ is the fishing effort in time t in country i.

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

$$\frac{dP_{i,t}}{dt} = \Delta P_i = P_{i,t} - P_{i,t-1} \tag{3}$$

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

$$P_{i,t} - P_{i,t-1} = rP_{i,t-1} - r\frac{P_{i,t-1}^2}{K_i} - Y_{i,t-1} \tag{4}$$

Dividing both sides of equation (4) by $P_{i,t-1}$, we arrive at the next equation

$$\frac{P_{i,t} - P_{i,t-1}}{P_{i,t-1}} = r - r\frac{P_{i,t-1}}{K_i} - \frac{Y_{i,t-1}}{P_{i,t-1}} \tag{5}$$

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

$$\frac{Y_{i,t}X_{i,t-1} - Y_{i,t-1}X_{i,t}}{Y_{i,t-1}X_{i,t}} = r - r\frac{Y_{i,t-1}}{K_i qX_{i,t-1}} - qX_{i,t-1} \tag{6}$$

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

$$Y_{i,t} = (1+r)\frac{Y_{i,t-1}X_{i,t}}{X_{i,t-1}} - \frac{r}{qK_i}\cdot\frac{Y_{i,t-1}^2 \cdot X_{i,t}}{X_{i,t-1}^2} - qX_{i,t}Y_{i,t-1} \tag{7}$$

We replaced $(1+r)$ by α, $-r/(qK_i)$ by β, and $-q$ by γ, and obtained *estimation model I* as follows:

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

where the sign of parameter α is positive and $\alpha \geq 1$ (because $\alpha = (1+r)$, and $r \geq 0$), and the signs of β and γ are definitely negative. Here, note that we assume K_i are identical and constant in each country ($K_i = \overline{K}$) (6).

Next, we assume that the catchability coefficient q is different for each country i: q_i. Then, equation (7) can be rewritten as follows:

$$Y_{i,t} = (1+r)\frac{Y_{i,t-1}X_{i,t}}{X_{i,t-1}} - \frac{r}{q_iK_i}\cdot\frac{Y_{i,t-1}^2\cdot X_{i,t}}{X_{i,t-1}^2} - q_iX_{i,t}Y_{i,t-1} \tag{9}$$

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

$$Y_{i,t} = \alpha\frac{Y_{i,t-1}X_{i,t}}{X_{i,t-1}} + \beta_i\frac{Y_{i,t-1}^2\cdot X_{i,t}}{X_{i,t-1}^2} + \gamma_iX_{i,t}Y_{i,t-1} \tag{10}$$

Definitely, β_i and β_j equal $-r/(q_iK_i)$ and $-r/(q_jK_j)$, respectively and we assume $K_i = K_j = \bar{K}$, therefore β_i can be substituted by β_j as follows:

$$\beta_i = \frac{-r/(q_iK_i)}{-r/(q_jK_j)}\beta_j = (\frac{q_i}{q_j})^{-1}\beta_j = (1+\frac{q_i-q_j}{q_j})^{-1}\beta_j = (1+d_i)^{-1}\beta_j \tag{11}$$

where d_i is $(q_i-q_j)/q_j$.

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

$$\gamma_i = \frac{-q_i}{-q_j}\gamma_j = (\frac{q_i}{q_j})\gamma_j = (1+\frac{q_i-q_j}{q_j})\gamma_j = (1+d_i)\gamma_j \tag{12}$$

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

$$Y_{i,t} = \alpha\frac{Y_{i,t-1}X_{i,t}}{X_{i,t-1}} + \beta_j(1+d_i)^{-1}\frac{Y_{i,t-1}^2\cdot X_{i,t}}{X_{i,t-1}^2} + \gamma_j(1+d_i)X_{i,t}Y_{i,t-1} \tag{13}$$

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

$$\begin{aligned} Y_{i,t} = \alpha\frac{Y_{i,t-1}X_{i,t}}{X_{i,t-1}} &+ \beta_j(1+\sum_i d_i\cdot dummy_i)^{-1}\frac{Y_{i,t-1}^2X_{i,t}}{X_{i,t-1}^2} \\ &+ \gamma_j(1+\sum_i d_i\cdot dummy_i)X_{i,t}Y_{i,t-1} \end{aligned} \tag{14}$$

where the sign of parameter α is positive and $\alpha \geq 1$ (because $\alpha = (1+r)$ and $r \geq 0$), and the signs of $\beta_j(1+\sum_i d_i\cdot dummy_i)^{-1}$ and $\gamma_j(1+\sum_i d_i\cdot dummy_i)$ are negative for all i.

By applying *estimation model I* [equation (8)] or *II* [equation (14)] to the OECD cross-country data, we can determine whether or not the Schaefer model can be applied to macro data.

Additionally, we can estimate relative biomass (P_t/K) using the estimated parameters (α, β and γ) of the above two models. In *estimation model I*, we calculate relative biomass (P_t/K) using

$$P_t = \sum_i P_{i,t} = \sum_i \left(\frac{Y_{i,t}}{qX_{i,t}}\right) \tag{15}$$

gained from equation (2) and

$$K = \sum_i K_i = \sum_i \left(-\frac{r}{q\beta}\right) = -\frac{r}{q\beta} \cdot i \tag{16}$$

gained from equation (8). Here q is given as $-\gamma$ and the γ is estimated in equation (8).

In *estimation model II,* we calculate relative biomass (P_t/K) using P_t obtained from

$$P_t = \sum_i P_{i,t} = \sum_i \left(\frac{Y_{i,t}}{q_i X_{i,t}}\right) \tag{17}$$

and K obtained from

$$K = \sum_i K_i = \sum_i \left(-\frac{r}{q_i \beta_i}\right) \tag{18}$$

gained from equation (10).

In the following, we estimate above two relative biomass indicators and weigh the consequences.

3. The data

To check the feasibility of the model, data from developed countries were used due to their availability. Data were obtained primarily from "Fishstat" (FAO) and "Review of Fisheries in OECD Countries" (OECD). Table 1 shows the descriptive statistics of the relevant variables. Fish catch is denoted as Y, and the root of the product of the number of vessels and the number of labors as X[(8)]. Data from 22 OECD countries between 1998 and 2007 are available, but some values are missing. As a result, the number of observations totaled 155.

4. Results

4-1. Estimation results

Table 2 shows the results for *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* was ordinary least squares (OLS) and that for *estimation model II*

Table 1 Descriptive statistics

	Fish catch [Y] <1,000 tonnes>	Fishing effort [X] < - >	Vessels [-] <GRT/GT>	Labors [-] <Number>
Average	1,008	102,414	273,121	45,567
S. D.	1,223	144,996	343,334	72,798
Min.	20	3,104	15,425	481
Max.	5,315	654,890	1,548,071	277,042
No. of obs.	155	155	155	155
Source	FAO "Fishstat"	(Vessels x Labors)$^{1/2}$	OECD "Review of Fisheries in OECD Countries"	OECD "Review of Fisheries in OECD Countries"

Notes:

1) [ ] and < > indicate variables and units, respectively.

2) We supplemented the missing Japanese data from other available sources: The Ministry of Agriculture, Forestry and Fisheries (MAFF) "Survey on Marine Fishery Production"(8) for fish catches; Fisheries Agency "Statistic Tables of Fishing Vessels (General Reports No.59, as of the end of 2006)"(9) for vessels; Ministry of Agriculture, and Forestry and Fisheries (MAFF) "Survey of Persons Engaged in Fishery"(10) for labors. However, this supplement had little impact on the estimation results.

was non-linear least squares (NLS).

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

For the result of *estimation model II,* which considers the effect of each country's catchability coefficient as the dummy variables, the estimate of α is positive and $\alpha \geq 1$, and the estimates of β and γ are negative. α and γ are statistically significant at the 1% level, but β is not significant at the 10% level (further data collection may be needed to improve the significance of β, because we use relatively large numbers of dummy variables). These signs are consistent with the theoretical rationale. With regards to the dummy variable coefficients, 18 out of 21 are significant, and the 18 coefficients are larger than -1; this is desirable from the theoretical sign condition [see, equation (14)]. The determination coefficient, R^2, is 0.915 and $adj.R^2$ is 0.900, and the model's indicator of fitness is sufficiently large.

Table 2 Estimation results

	Estimation model I			Estimation model II		
Parameter	Estimate		(t-value)	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)		

Notes:

1) $*P < 0.10$, $** P < 0.05$, $*** P < 0.01$.

2) The benchmark of $d_j (j = 1, \ldots, 21)$ is Turkey.

3) R^2 values are calculated as the square of the correlation coefficient between the observation value and the estimation value of fish catch (Y). The values of $adj. R^2$ are calculated as $1-(1-R^2) \times (n-1)/(n-k)$, where n is the number of observations and k is the number of independent variables. For further details, see Minotani and Maki (2010), p.205.

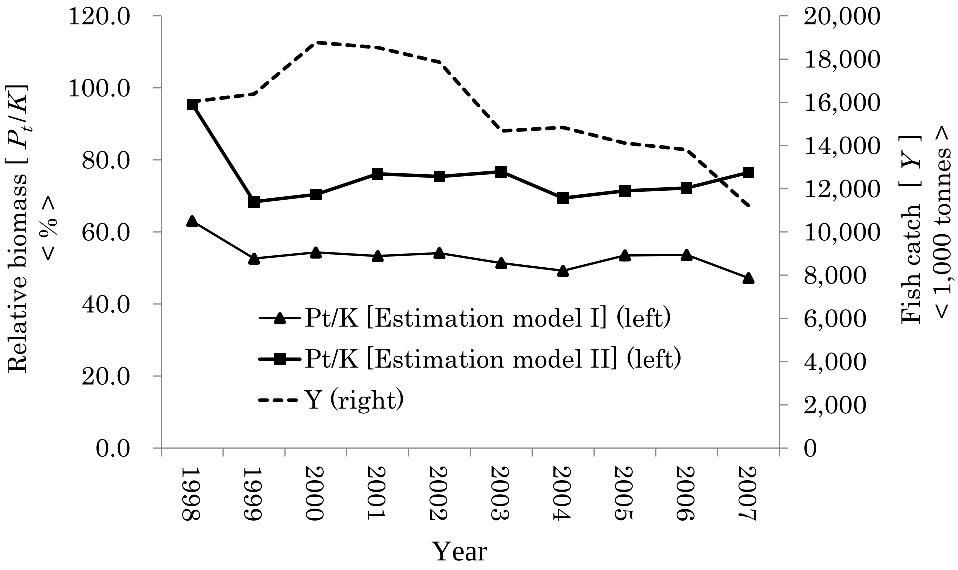

Figure 1 Relative biomass

4-2. Relative biomass

Figure 1 shows the result of the simulation of relative biomass (P_t/K). Relative biomass simulated from *estimation model I* has a value close to 0.5. Relative biomass simulated from *estimation model II* goes around 0.75 in a large sense. This difference could be explained by the fact that the value of β, as estimated by *estimation model II* in Table 2, is not significant. Therefore, *estimation model II* requires further data to conduct a more rigorous simulation despite the existence of the favorable feature that it bases on country specific catchability coefficient q_i.

In any case, the ratio of global fish biomass to carrying capacity approximately ranges from 0.5 to 0.75 in our study. These results are consistent with those of the existing study targeting *Hippoglossus stenolepis* on the North American west coast (Tanaka (2012), p. 67), in which relative biomass was estimated as having a value close to 0.5 between 0.25 and 1.

5. Conclusion

In this study, we developed a model to estimate global fish biomass using the conventional Schaefer model (where catchability coefficient q is constant) and is used to estimate country-specific catchability coefficients (q_i) as well as annual changes in relative biomass, which represents the ratio of fish stocks to carrying capacity. The results indicated that the Schaefer model can comfortably fit the macro data from

OECD countries. Our results also revealed that relative biomass approximately fluctuated from 0.5 to 0.75 between 1998 and 2007. These results are consistent with the existing study targeting a single species (Tanaka (2012), p.67).

Simultaneously, several limitations on the outcomes of this study must be highlighted. First, this study is not based upon a species-by-species approach, but rather showed annual macro-level changes of biomass for aggregated fish stocks subject to commercial fishing. In this sense, this study's methodology can only be used as a tool to provide supplemental information on the status of fish stocks rather than substitute it for scientific works engaged in collecting species-by-species scientific data. Second, although the catchability coefficient can be understood as the relative efficiency of a given country's fishery operations, it may include factors such as distance between fishing grounds and home ports or fishing vessels average size. The catchability coefficient, therefore, should not necessarily be considered to represent the efficiencies of a country's fishing industry. Third, this study assumes that intrinsic fish stock growth rate and environment's carrying capacity are constant among each country. These theoretical constraints should be relaxed in future challenges, for example by assigning specific values exogenously. Forth, this study only used data from OECD countries. In addition, some data were unavailable for some OECD countries in certain years, and the number of countries varies. Considering the fact that non-OECD countries and economies make significant contributions to global fishery production, future studies using more complete data, including non-OECD members, would be desirable.

Notes

(1) For the explanation on the Schaefer or the surplus production model based on the logistic growth function from the viewpoint of resource economics, see Clark (2010), pp.14-22 and Conrad (2010), pp.75-131.

(2) Nose *et al.* (1988), p.82 indicate that an estimation result of Pella and Tomlinson model are relatively similar to those of the Schaefer model under the equilibrium assumption.

(3) Richer model in reproduction theory is similar to the Schaefer model, but this model is typically used for species with non-overlapping generations, such as the various Pacific salmon species (Clark (2006), p.32). This model follows theoretically different assumptions against surplus production models such as the Schaefer model, which assume overlapping generation by considering both recruitment and growth. On

reproduction theory, see also Nose *et al.* (1988), pp.185-194.

(4) Takarada (2009) theoretically analyzes the effects of country specific catchability coefficients under a two-country model. Here our contribution is to develop an econometric model to estimate country specific catchability coefficients and use it under an empirical approach.

(5) We referred to Ariji (2004), p.143 with regard to the Schaefer model under the assumption that fish biomass is not at equilibrium. See also Nose *et al.* (1988), pp.72-73. We referred Tanaka (2012), pp.61-62 for the notation of each variable.

(6) Some previous studies argue that γ and K differ according to each country (e.g., Rus (2012), see also Brander and Taylor (1998), Dong and Takarada (2010)). On the other hand, Tanaka (2012), p.70 indicates that the habitat density of fishery resources is basically non-uniformly-distributed even in a specific area. The assumption of identical and constant γ and K among each country is a restriction in this study, but the remediation is challenges for future. See also McWhinnie (2009) which assumes constant γ and K for the whole earth.

(7) Ariji (2004), p.112 indicates that fishing effort can be expressed as a multiplication of plural input variables. Here the number of vessels and that of labors are not flows but stocks, because both of them are values at a certain point.

(8) URL: http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001061498 (Accessed in April 2014)

(9) URL: http://www.library.maff.go.jp/GAZO/60002481/60002481_02.pdf (Accessed in April 2014) The data of tidal waters fishery (p.22, p.23) are used in the study.

(10) URL: http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001061630 (Accessed in April 2014)

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