Development of a marine ecosystem dynamic computable general equilibrium model and its application to a fishery depression problem

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***Abstract*—** This study provides a methodology to assess the long term economic activity and natural resource stock. Application of the methodology for the case of depression in the Japanese clam fishery assists in finding better measures for regional sustainable development. The conventional renewable resource stock model is extended to consider an environmental variation, which may have become an adverse factor for resource depletion and the resultant fishery depression. Considering previous qualitative findings, the model assumes that feeding damage established after the fishery releases seedlings for the clam stock increase is the cause of the depression. A dynamic two-country model is combined with the resource stock model, and then sequentially solved. Following model verification, an empirical study on clam fishery depression is conducted to estimate the long term regional economic output of the industry and the clam stock. Furthermore, the current clam resource stock and the reason for the occurrence of the clam fishery depression are determined. The relationship between feeding damage by seedling release and overexploitation of the clam resource is reasonably discussed.

***Keywords*—** computable general equilibrium model, fishery economics, predator-prey ecosystem, sustainable development.

I. Introduction

The worldwide crisis of loss of vital renewable aquatic resources is a major concern because of the difficulty of sustainable fishing practices, as pointed out by Clark [1] and Worm *et al*. [2]. By 2008, the percentage of world fishery overexploitation increased to 30% and the share of fisheries without abundant aquatic resources was 80%, according to the Food and Agriculture Organization of the United Nations (FAO) [3].

In Japan, the catch of the Manila clam (*Tapes philippinarum*) was consistent at around 140 million tons in the 1980s; however, it decreased drastically to approximately 3 million tons in the 2000s [4]. Moreover, there is no prospect for fishing recovery with this species, despite the continually small catch. This fact poses a serious social, economic, and environmental problem. Hence, some environmental variation should be considered in relation to the detection of the causes not connected with overexploitation. Consequently, the Coastal Fisheries Promotion Council developed guidelines in 1997 for the development project of Manila clam growth. The Fisheries Agency then established the National Council of Manila Clam Resources in 2003.

Kakino [5] has indicated a wide-range of possible causes for clam resource depletion, including water temperature, bottom sediment, dissolved oxygen, lack of food, emergence of predators, and overexploitation. Fig. 1 illustrates possible factors that influence the clam fishery and ranges in application of models. However, a solution to the resource crisis has not yet been developed, because of a complex web of interactions and lack of methodology to assess the resource state from an environmental–economic perspective.

Previous research on marine life analyzes aquatic resource economics and fish ecosystems separately. For the renewable resource economic model, Gordon [6] and Schaefer [7] applied a logistic function to the natural growth rate of the fish for determining the optimum catch. Schaefer [7] utilized actual ocean data to investigate the relationship between fishing effort and fish population growth. Clark [8], Dasgupta [9], and Dasgupta and Maler [10] developed a model to describe the process of destruction of the fish. However, those models consider the aquatic resource depletion caused by overexploitation and have not explicitly mentioned environmental variation and other factors that may play a role in accelerating resource depletion. The previously described clam fishery depression is beyond the description of the conventional resource economic model because the continually small catch cannot realize the subsequent large catch.

There are many marine life ecosystem models such as the biochemical model that focuses on the predator–prey system (Kuang and Beretta [11], Hsu *et al*. [12], Tanaka and Mackenzie [13], Ruan *et al*. [14]) and the dynamic model of ecosystems (Bald *et al*. [15]). However, these models are complex because of the many model parameters required. In addition, they do not consider the interactions between the ecosystem and fishery economics.

Previous ecological and economic models may provide a key to solving the crisis of fish resources under environmental variation. To investigate the reason for the fishery depression, it is necessary to assume its main cause from something social and scientific informative in relation to the fishery depression and then to combine appropriate ecological and theoretical economic models. Then, with the help of the model, the causal analysis can be conducted quantitatively. Furthermore, the economic and environmental impacts of environmental variations can be assessed for a significant step in the environmental remediation and economic recovery process.

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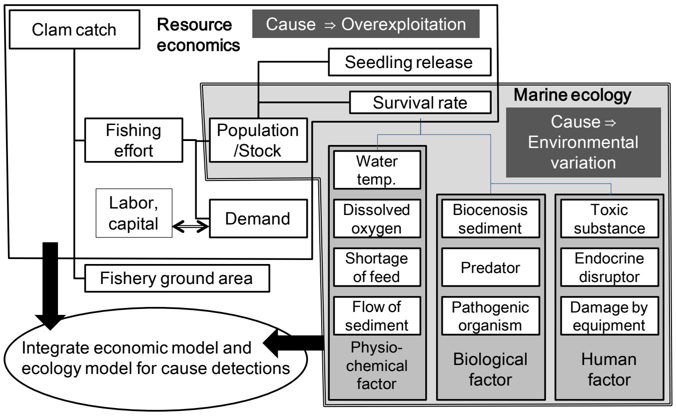

Fig. 1 Factors influencing clam fishery depression and ranges in application of models

This study aims to elucidate the causes of the recent depression in the Japanese clam fishery by focusing on analyzing clam resource management under the environmental variation of predator emergence. Thus, an empirical study is performed to investigate causes of the clam fishery depression in Maizuru Bay, Japan. A feasible policy measure that recovers resources and rebuilds the regional economy should be sought, following the identification of the causes of resource depletion.

Previous policy studies of sustainable development and its feasibility address the interrelated problem between the environmental resource stock and economic activities in multiple elements: the product, regional, national, and international levels. Many of them focus on restructuring measures for the social system, e.g., the necessity to quantify the social costs of environmental damage and enhance one's respect for environmentally friendly social norms [16], the concept of the urban–rural interface for natural risk management [17], the problem of water resource shortage incurred by rapid urbanization [18], and the development of indicators to measure the economic activity compatible with the rural environment [19].

Any related study needs to quantify the long-term economic output, natural resource stock, and environmental damage by applying a comprehensive environmental-economic model. Therefore, this study aims to develop a comprehensive ecological, socio-economic model using a computable general equilibrium (CGE) model, i.e., a two-country model [20], [21]. This paper describes the detailed procedure of the numerical calculations and estimation results that have not been covered in previous papers [22].

Section II provides an overview of the current state and the previous findings of the Manila clam fishery depression in Maizuru Bay, Japan. This is background for performing an empirical study on the fishery depression problem. Section III describes the basic model formulation by following a two-country model. The conventional fishery economic model is extended such that the Michaelis–Menten-type ratio-dependent predator–prey model is added. Sections IV and V describe calibration of the developed ecologically dynamic CGE model and the model verification, respectively. Section VI discusses the current clam resource stock and the causes of the development of clam fishery depression.

II. Previous Findings for Clam Fishery Depression

The catch trend of the Manila clam fishery in Maizuru Bay in the northern Kyoto Prefecture, Japan, is shown in Fig. 2. According to a report by Japan's Ministry of Agriculture, Forestry and Fisheries [4], the catch was maintained at around 200 tons in the 1980s. However, the catch decreased since 1993 and drastically declined to 38 tons in 1998. The subsequent catch remained at the same level until 2002. Between 2003 and 2006, the catch was only at a few tons annually.

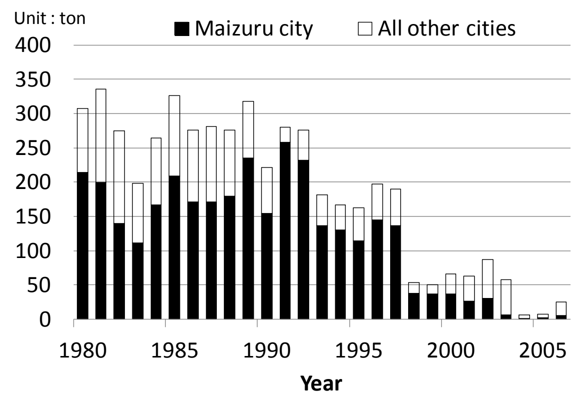

Fig. 2 Clam catch trend in the Kyoto Prefecture [4]

The 1996 report [23] noted that many of the dead clams were found without seashell damage probably because they were the prey of starfish (*Astropecten polyacanthus*). The 2010 report [24] concluded that the causes of clam resource depletion remained less popular, although the following observations are noteworthy. The period of seedling release coincides with that of the steep clam catch decline. It was also determined that most of the seedlings were from other regions. The latter fact may illustrate that clam death could be caused by infection by a parasite (*Perkinsus protozoan*) and the incorporation of a predator (*Euspira fortunei*). In addition, Ueno investigated the influence of treated sewage [25] and sludge sedimentation [26] on fishery depression.

Against this background, this study assumes that the emergence of a predator–prey system after the seedling release is one of the most liable reasons for the clam fishery depression.

III. Method

A. Two-country Model

A causal analysis is conducted using the developed two-country model that considers clam growth with regard to the predator–prey ecological system. Two regions are assumed to be those where households and firms interact in a perfectly competitive market with two commodities. The two commodities consist of the clams and other goods produced by

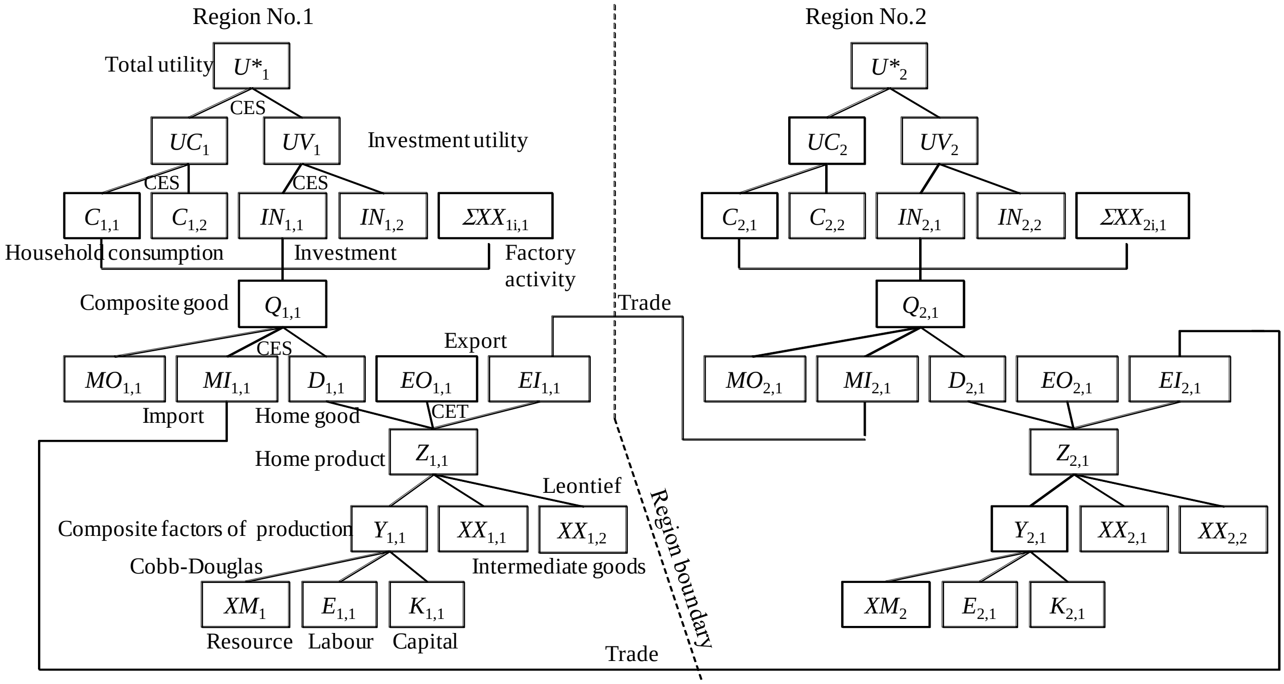

Fig. 3 Two-country model structure

the clam fishery firm (i = 1) and other industrial firms (i = 2), respectively.

One region (k = 1) represents Maizuru City, where the clam catch depression is encountered. On the other hand, the other region (k = 2) represents all cities in the Kyoto Prefecture, except Maizuru City. These regions are assumed to be small countries. All model variables have the subscripts i and k.

The market is described by the CGE model that is compatible with the input–output tables. The model structure is illustrated in Fig. 3.

B. Factors of Production

Assuming open market access, the clam fishery produces composite factors with zero profit. The Cobb–Douglas function is extended to include the inputs of production factors and clam resources.

$$\pi_{k,1}^{y} = p_{k,1}^{y}\, Y_{k,1} - \left(w_k E_{k,1} + r_k K_{k,1}\right) = 0 \tag{1}$$

$$Y_{k,1} = q_{k,1} E_{k,1}^{\sigma_{k,1}} K_{k,1}^{\left(1-\sigma_{k,1}\right)} XM_k \tag{2}$$

where p^y: price of composite factors, Y: production of composite factors, w: wage, E: labor, r: rent, K: capital, XM: resource stock, and q and σ: parameters.

For a group of industries other than the clam fishery, it is assumed that firms act to maximize their profits in the input of the factors of production.

$$\max.\left(p_{k,2}^{y}\, Y_{k,2} - w_k E_{k,2} - r_k K_{k,2}\right) \tag{3}$$

$$\text{s.t. } Y_{k,2} = q_{k,2} E_{k,2}^{\sigma_{k,2}} K_{k,2}^{\left(1-\sigma_{k,2}\right)} \tag{4}$$

C. Home Production

The Leontief production function [27] is applied to represent the production of regional output Z with fixed proportions of composite factors Y and intermediate inputs XX.

$$\max.\left(p_{k,i}^{z}\; Z_{k,i} - p_{k,i}^{y} Y_{k,i} - \sum_{l=1}^{NB} p_{k,l}^{q}\; XX_{k,l,j}\right) \tag{5}$$

$$\text{s.t. } Z_{k,j} = \min.\left\{ \frac{Y_{k,j}}{ay_{k,j}}, \frac{XX_{k,1,j}}{ax_{k,1,j}}, \frac{XX_{k,2,j}}{ax_{k,2,j}} \right\} \tag{6}$$

where ax: intermediate input coefficient, ay: input coefficient of composite factors, and p^z: price of home goods.

D. Trade

It is assumed that to maximize their profits, firms obtain production goods from home region Z and supply to home region D and other regions EI and EO. Other regions consist of regions other than Maizuru City and regions not listed previously, i.e., other prefectures and foreign countries. The problem can be written as follows:

$$\max.\left(p_{k,i}^{eo}\; EO_{k,i} + p_{k,i}^{ei}\; EI_{k,i} + p_{k,i}^{d}\; D_{k,i} - p_{k,i}^{z}\; Z_{k,i}\right) \tag{7}$$

$$\text{s.t. } Z_{k,i} = \vartheta_{k,i}\left(\delta eo_{k,i}\; EO_{k,i}^{\;\phi_{k,i}} + \delta ei_{k,i}\; EI_{k,i}^{\;\phi_{k,i}} + \delta d_{k,i}\; D_{k,i}^{\;\phi_{k,i}}\right)^{\frac{1}{\phi_{k,i}}} \tag{8}$$

where *EI*: exports into the region defined by the two-country model, *EO*: exports into regions other than the two countries, p^{ei} and p^{eo}: the corresponding export prices, and p^{d}: home price. Applying the Armington assumption [28], the output transformation is defined as the constant elasticity of transformation (CET) function with the scale parameter ϑ and the export share parameters δei , δeo , and δd .

Moreover, it is assumed that firms maximize their profits by mixing home goods and imported goods, i.e., *MI* and *MO*, respectively, and then producing composite goods *Q*. This problem can be written with the constant elasticity of substitution (CES) function.

$$\max.\left(p^{q}_{k,i}\ Q^{q}_{k,i}-p^{mo}_{k,i}\ MO_{k,i}-p^{mi}_{k,i}\ MI_{k,i}-p^{d}_{k,i}\ D_{k,i}\right)\quad(9)$$

$$\text{s.t. } Q_{k,i}=\gamma_{k,i}\left(\xi mo_{k,i}\ MO_{k,i}{}^{\eta_{k,i}}+\xi mi_{k,i}\ MI_{k,i}{}^{\eta_{k,i}}+\xi d_{k,i}\ D_{k,i}{}^{\eta_{k,i}}\right)^{\frac{1}{\eta_{k,i}}}\quad(10)$$

where γ : the scale parameter, and ξmi , ξmo , and ξd : import share parameters.

E. Households

Households maximize their utility by their commodity consumption and savings, subject to household budget constraints. It is assumed that savings is equal to investments. Substitutions between (1) two commodities, (2) two investments, and (3) the total commodity and total investment are individually given by the CES function as follows:

$$\max. UC_k=\max.\left\{\alpha_k C_{k,1}^{(\varphi_k-1)/\varphi_k}+(1-\alpha_k)C_{k,2}^{(\varphi_k-1)/\varphi_k}\right\}^{\varphi_k/(\varphi_k-1)}\quad(11)$$

$$\text{s.t. } DI_k=\sum_{m=1}^{2}\left(p^{q}_{k,m}C_{k,m}+p^{v}_{k,m}IN_{k,m}\right)-\varepsilon_k SI_k-\varepsilon_{3k}SO_k\quad(12)$$

where *UC*: consumption utility, *C*: consumption of commodity, α, φ: parameters, *DI*: household budget, *IN*: investment, p^q and p^v: commodity price and investment price, respectively, and $SI(\varepsilon)$ and $SO(\varepsilon_3)$: the current account (exchange rate) of two countries and the current account (exchange rate) of the other regions, respectively.

$$\max. UV_k=\max.\left\{a_k IN_{k,1}^{(f_k-1)/f_k}+(1-a_k)IN_{k,2}^{(f_k-1)/f_k}\right\}^{f_k/(f_k-1)}\quad(13)$$

where *UV*: investment utility, and a and *f*: parameters.

$$\max. U^*_k=\max.\left\{u_k C_k^{*(\omega_k-1)/\omega_k}+(1-u_k)IN_k^{*(\omega_k-1)/\omega_k}\right\}^{\omega_k/(\omega_k-1)}\quad(14)$$

$$\text{s.t. } DI_k=p^{*q}_k C^*_k+p^{*v}_k IN^*_k-\varepsilon_k SI_k-\varepsilon_{3k}SO_k\quad(15)$$

where *U**: total utility, *C**: total consumption, *IN**: total investment, u, ω : parameters and p^{*q} and p^{*v}: total commodity and total investment prices, respectively.

F. Equilibrium Conditions

Equations (16)-(20) should be considered to ensure the supply-demand balance, total consumption, total investment, total labor and total capital, respectively.

$$Q_{k,i}=C_{k,i}+IN_{k,i}+\sum_{m=1}^{2}XX_{k,i,m}\quad(16)$$

$$C^*_k=\sum_{m=1}^{2}C_{k,m}\quad(17)$$

$$IN^*_k=\sum_{m=1}^{2}IN_{k,m}\quad(18)$$

$$\overline{E}_k=\sum_{m=1}^{2}E_{k,m}\quad(19)$$

$$\overline{K}_{k,i}\Big|_{t+1}=\left(1-\delta_{k,i}\right)\overline{K}_{k,i}\Big|_{t}+IN_{k,i}\Big|_{t}\quad(20)$$

where δ : the depreciation ratio of capital. The constant depreciation ratio could not be given from the estimated capital data. Thus, the corresponding capital data is utilized in place of (20).

For trade, the following equations need to be considered: the export–import balance in (21) and (26); the trade price equilibrium of foreign currency in (22); the trade price equilibrium with currency exchange rates in (23), (24), (27), and (28); and the inter-regional trade balance in (25) and (29).

$$EI_{k,i}=MI_{l\neq k,i}\quad(21)$$

$$p^{We}_{k,i}=p^{Wm}_{l\neq k,i}\quad(22)$$

$$p^{ei}_{k,i}=\varepsilon_k p^{We}_{k,i}\quad(23)$$

$$p^{mi}_{k,i}=\varepsilon_k p^{Wm}_{k,i}\quad(24)$$

$$\sum_{m=1}^{2}p^{We}_{k,m}EI_{k,m}+SI_k=\sum_{m=1}^{2}p^{Wm}_{k,m}MI_{k,m}\quad(25)$$

$$EO_{k,i}=MO_{l\neq k,i}\quad(26)$$

$$p^{eo}_{k,i}=\varepsilon_{3k}p^{W3e}_{k,i}\quad(27)$$

$$p^{mo}_{k,i}=\varepsilon_{3k}p^{W3m}_{k,i}\quad(28)$$

$$\sum_{m=1}^{2}p^{W3e}_{k,m}EO_{k,m}+SO_k=\sum_{m=1}^{2}p^{W3m}_{k,m}MO_{k,m}\quad(29)$$

G. Marine Life Stock Model

For the clam, a conventional equation for the renewable resource stock has two parts, the natural growth rate of the resource stock *F* and the catch *Z* [6]. Equation (30) shows that the conventional resource stock equation is extended to add two

Table 1 The 1980 SAM in Maizuru city, k = 1

			Expenditures								Unit: Million JPN
			Factory activity		Factors of Production		Final consumption	Investment	Export		Total
			Clam fishery	Others	Labor	Capital			Rest of the world	Kyoto	
Receipts	Factory activity	Clam	0	9			6	0	33	12	60
		Others	24	188,344			186,231	56,559	146,112	19,461	596,729
	Factors of production	Labor	18	217,936							217,954
		Capital	6	45,102							45,108
	Final consumption				217,954	45,108					263,062
	Investment						76,825		-838	-19,428	56,559
	Import	Rest of the world	12	145,295							145,307
		Kyoto	0	44							44
	Total		60	596,729	217,954	45,108	263,062	56,559	145,307	44	

Table 2 The 1980 SAM in all other cities, k = 2

			Expenditures								Unit: Million JPN
			Factory activity		Factors of Production		Final consumption	Investment	Export		Total
			Clam fishery	Others	Labor	Capital			Rest of the world	Kyoto	
Receipts	Factory activity	Clam	0	149			156	0	14	0	320
		Others	10	4,322,650			4,637,268	1,408,344	3,627,688	44	13,996,005
	Factors of production	Labor	8	5,001,990							5,001,998
		Capital	3	1,033,812							1,033,815
	Final consumption				5,001,998	1,033,815					6,035,813
	Investment						1,398,388		-9,472	19,428	1,408,344
	Import	Rest of the world	287	3,617,943							3,618,230
		Kyoto	12	19,461							19,472
	Total		320	13,996,005	5,001,998	1,033,815	6,035,813	1,408,344	3,618,230	19,472	

terms, i.e., the incremental rate by seedling release, GR_k, and the resource reduction rate by feeding damage, H_k. The clam stock in the next year, t + 1, is given with variables in previous year t.

$$XM_k\big|_{t+1} = XM_k\big|_t + F_k\big|_t - Z_{k,1}\big|_t + GR_k\big|_t - H_k\big|_t \tag{30}$$

$$F_k = -\overline{a_k} + \overline{b_k}\, XM_k\big|_t - \overline{c_k}\, XM_k\big|_t^2 \tag{31}$$

$$Z_{k,1} = \frac{Y_{k,1}}{ay_{k,1}} = \frac{q_{k,1} E_{k,1}^{\sigma_{k,1}} K_{k,1}^{(1-\sigma_{k,1})} XM_k\big|_t}{ay_{k,1}} \tag{32}$$

$$GR_k = (1 - p_{mk}) SE_k\big|_t \tag{33}$$

$$H_k = V_{xs\,k}\left(\frac{XM_k\big|_t}{K_{xs\,k} + XM_k\big|_t}\right) SS_k\big|_t \tag{34}$$

where $\overline{a}$, $\overline{b}$, and $\overline{c}$ in (31) are parameters and are related to the carrying capacity Ke.

$$Ke = \left(\overline{b} + \sqrt{\overline{b}^2 - 4\overline{ac}}\right) \Big/ \left(2\overline{c}\right) \tag{35}$$

It is assumed that the released young shells are safe to grow and they become the clam resource for the next year. A percentage of the predator mixed in the seedlings is defined as p_m ($0 \le p_m \le 1$).

In addition, the reduction of the clam stock is assumed to be subject to the predator–prey ecosystem. Equation (34) denotes the Michaelis–Menten-type ratio-dependent model [12] with V_{xs}: capturing rate, K_{xs}: half saturation constant, and SS_{xs}: total weight of the predator. The time unit is extended from one day to one year.

No data about the predator's weight, growth rate, or mortality currently exists. Therefore, the weight of the predator is assumed to be equivalent to the accumulated weight of the predator mixed in the released seedling.

$$SS_k\big|_t = \sum_{T=t_0}^{t} p_m SE\big|_T \tag{36}$$

IV. Model Calibration

A. Two-country Model

For the developed two-country model, the model calibration needs to be performed in the benchmark year to determine the model parameter and initial values. Furthermore, the input exogenous variables for the analytical period need to be determined.

The necessary data used in the economic model was obtained as follows. Fig. 4 illustrates the procedure used to determine the model parameters and exogenous variables. The 1980–2006 Kyoto Prefectural input–output tables in 1995 real value were obtained by a deflator. The prefectural input–output tables were rearranged for the clam fishery and other industries. Finally, the two regions' input–output tables and the social accounting matrix (SAM) were calculated by dividing the rearranged input–output tables and accommodating the supply–demand imbalances by the inter-regional trade data.

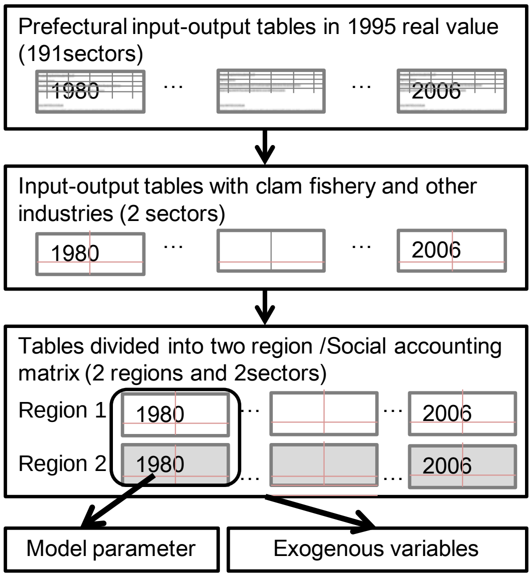

Fig. 4 Decision flow of the two-country model parameter and exogenous variable

Tables 1 and 2 illustrate the 1980 SAM in Maizuru City and all other cities in the Kyoto Prefecture, respectively. The model's parameters and initial endogenous variables are determined from the 1980 SAM so that the initial equilibrium condition can be satisfied. Table 3 illustrates the determined model parameters. Exogenous variables $\overline{E}$, $\overline{K}$, *SI*, and *SO* are determined from SAM of the period 1980–2006.

Table 3 Two-country model parameters in the 1980 SAM

Region k	1	1	2	2
Industry i	1	2	1	2
q_{ki}	3.022E+00	1.581E+00	1.511E-01	1.581E+00
σ_{ki}	5.000E-01	8.285E-01	5.000E-01	8.287E-01
ax_{k1i}	3.199E-03	1.941E-05	3.199E-03	1.439E-05
ax_{k2i}	4.951E-01	4.173E-01	4.951E-01	4.173E-01
ay_{ki}	5.017E-01	5.827E-01	5.017E-01	5.827E-01
ϕ_{ki}	1.250E+00	1.250E+00	1.250E+00	1.250E+00
δeo_{ki}	2.488E-01	2.856E-01	7.619E-02	5.315E-02
δei_{ki}	3.214E-01	4.728E-01	8.318E-01	9.013E-01
δd_{ki}	4.298E-01	2.415E-01	9.196E-02	4.554E-02
θ_{ki}	3.288E+00	3.414E+00	8.472E+00	1.290E+01
η_{ki}	7.500E-01	7.500E-01	7.500E-01	7.500E-01
ξmo_{ki}	5.413E-01	4.318E-01	5.434E-01	4.101E-01
ξmi_{ki}	5.223E-02	5.692E-02	2.443E-01	1.110E-01
ξmd_{ki}	4.065E-01	5.113E-01	2.123E-01	4.789E-01
γ_{ki}	2.068E+00	2.132E+00	2.209E+00	2.311E+00
Region k	1		2	
α_k	3.522E-08		3.522E-08	
φ_k	6.000E-01		6.000E-01	
a_k	1.297E-12		1.297E-12	
a_k	6.000E-01		6.000E-01	
u_k	8.793E-01		8.793E-01	
w_k	6.000E-01		6.000E-01	

B. Clam Stock model

There is no data for the clam resource stock in Maizuru Bay. The catch and production values of the clam fishery are available. To estimate the initial stock and parameters, the variable for resource stock *XM* in (30) is transformed into the variable of catch *Z* by (32). Model estimation was performed to minimize the square sum average of the errors between the estimated catch *Z* and the actual catch $\overline{Z}$.

$$\max f\left(Ke,\overline{b},\overline{c},V_{xs},K_{xs},p_m\right) = \sum_{t=1}^{NT-1}\left(Z_{k,1}\Big|_{t+1} - \overline{Z}_{k,1}\Big|_{t+1}\right)^2 \quad (37)$$

$$\text{s.t.}\quad Z_{k,1}\Big|_{t+1} = \left\{ s\big|_t Z_{k,1}\big|_t + F_k\left(Z_{k,1}\big|_t\right) - Z_{k,1}\big|_t + GR_k\big|_t - H_k\left(Z_{k,1}\big|_t\right)\right\} \Big/ s\big|_{t+1} \quad (38)$$

$$s\big|_m = ay_{k,1} \Big/ \left(q_{k,1} \overline{E}_{k,1}\Big|_m^{\sigma} \overline{K}_{k,1}\Big|_m^{1-\sigma} \right), \quad m = t, t+1 \quad (39)$$

The estimation successfully terminated with an average error of 30.9 tons. The other model parameters were as follows: $\overline{a}$ = 0.00863, $\overline{b}$ = 0.637, $\overline{c}$ = 0.0324, Ke = 19700 (ton/km^2), V_{xs} = 40.5 (/year), K_{xs} = 1760 (ton), p_m = 0.107, and the initial clam stock $XM_k\big|_1$ = 772 (ton).

The estimated carrying capacity was close to the upper limit of the habitat density of 24000 (ton/km^2), which was reported by the survey [23]. Therefore, the estimation result is said to be reasonable. The estimation result also showed that the predator accounted for 10.7% of the released seedling.

V. Model Verification

A. Numerical Calculation Procedure

The applicability of the developed model is examined by considering the clam fishery depression described in Section II.

The two-country model has 120 variables that need to be solved; Y_{ki}, E_{ki}, K_{ki}, Z_{ki}, EI_{ki}, EO_{ki}, D_{ki}, Q_{ki}, MI_{ki}, MO_{ki}, C_{ki}, IN_{ki}, $p^y{}_{ki}$, $p^z{}_{ki}$, $p^q{}_{ki}$, $p^{ei}{}_{ki}$, $p^{eo}{}_{ki}$, $p^d{}_{ki}$, $p^{mi}{}_{ki}$, $p^{mo}{}_{ki}$, $p^v{}_{ki}$, $p^{We}{}_{ki}$, $p^{Wm}{}_{ki}$, XX_{kij}, XM_k, IF_k, C^*_k, IN^*_k, r_k, w_k, $p^{q*}{}_k$, $p^{v*}{}_k$, ε_k, ε_{3k} (k = 1, 2; i = 1, 2; j = 1, 2), and the same number of equations; the model contains three redundant equations, because of the Walras' law for two regions and an inter-regional balance. Therefore, with the assumption that the following three variables w_1, w_2, and ε_2 are exogenous, 117 endogenous variables were completely solved. All economic quantities are given as the quantity per capita. The solved price is a relative value. To discuss the change in a clam price, the initial values of all prices are assumed to be the same as the unit price in the 1980 production value of the clam fishery. In addition, price variables $p_{k,i}^{W3e}$ and $p_{k,i}^{W3m}$ are treated as exogenous.

The analytical period was set as 1980–2006. The model calculation was performed every year by the multiplier method [29]. By setting a regional household utility function as the object function, the dynamic CGE model was sequentially solved within a convergence tolerance of 0.001 for the equality and inequality constraints. A time step was subdivided under the condition that the maximum increment of exogenous variables became a value within 10%. As a result, the numerical calculation could be performed successfully.

Figs. 5 and 6 illustrate the required calculation time for a year and the resultant residual error for a calculation step. These figures illustrate that the model calculation was suitably terminated.

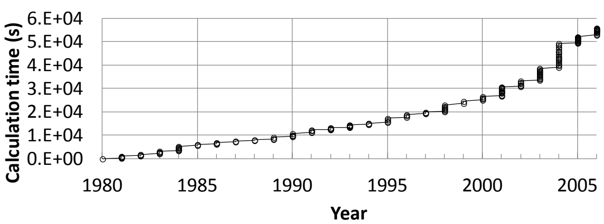

Fig. 5 Time required for convergence calculation

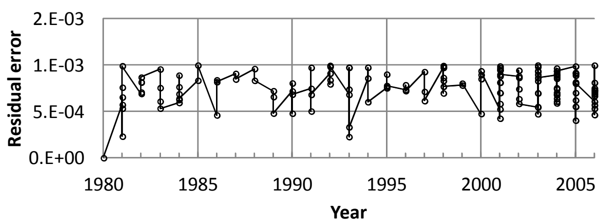

Fig. 6 Residual error of numerical calculation

B. Results

Figs. 7 and 8 show the comparison charts between estimated and actual values of regional production in the clam fishery and other industries, respectively. It is found that the trend of variation in the estimated value is consistent with the actual trend across the entire period. The average relative error for 27 years is less than 23% in the clam fishery and less than 5% in other industries. A large difference between actual and estimated production values is observed in the middle of the analytical period, because of a small change in the price. Indeed, there may be room for improvement in the model estimation by the application of the data assimilation method, but it can be said that on the whole, a comparatively good estimation is achieved.

Fig. 9 illustrates the clam price and catch relationship in Maizuru City. The reason for the distribution width in the clam price under the same catch can be rationally explained. More specifically, the clam price p^z depends on not only the clam catch Z but also other economic quantities such as p^d and D that satisfy the equilibrium condition of the substitution problem of the production Z, the supply D, and the amount of exports EI and EO. From the comparison of the actual and estimated relationships, it can be said that the price–catch relationship is reasonably estimated with the same range for the actual price.

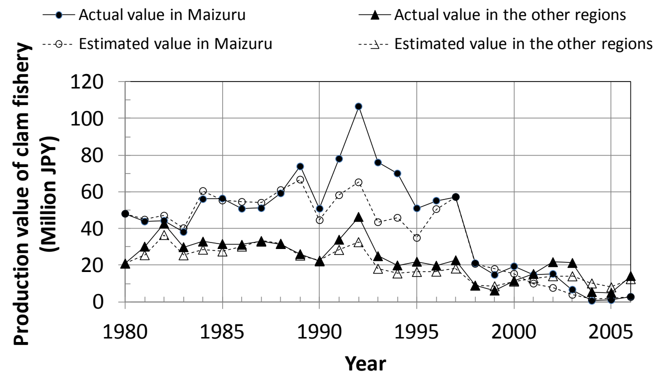

Fig. 7 Production value of clam fishery

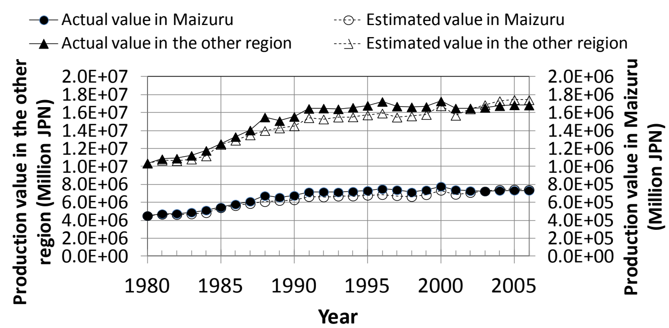

Fig. 8 Production value of other industries

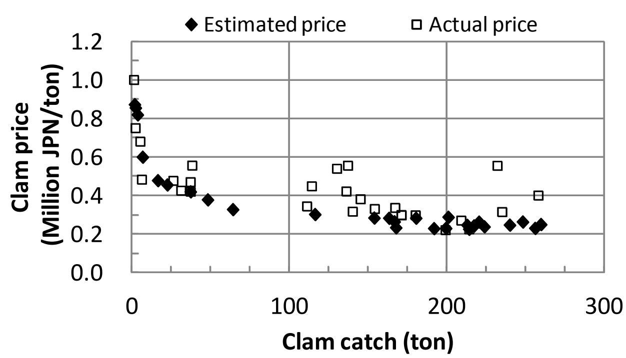

Fig. 9 Clam price and catch relationship

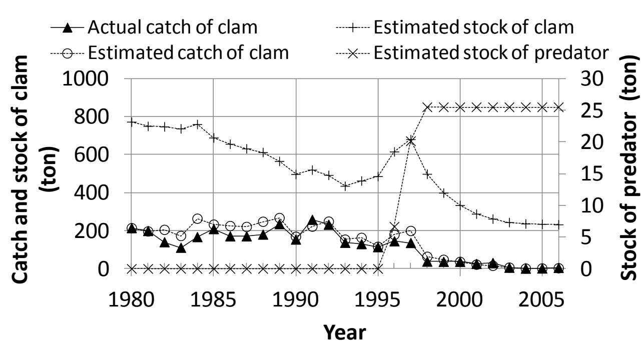

Fig. 10 Estimated stock and catch of clams

Fig.10 illustrates the trends in the estimated catch and actual catch in clam, estimated clam stock, and estimated predator stock in Maizuru Bay. It can be said that the catch of clam is suitably estimated with an average error of 26.9 tons.

VI. Discussion

A. Clam Resource Depletion

Fig. 10 illustrates that there are two periods of reduction in the clam stock. A slow decline in the clam stock is observed in the period 1985–1993. However , the clam stock trend shifts and increases in the period 1994–1995, thereby reducing the actual catch that falls below the natural growth increment in the period 1993–1995; this may be a sign of clam stock recovery.

However, resource depletion without a sign of stock recovery since 1998 is estimated. During the same period of seedling release, the estimation result shows that the stock of the predator increases rapidly, while the stock of the prey clam decreases.

The current clam stock level appears to be stabilized, but the corresponding stock is at a lower level of 70% of the estimated steady stock in the 1980s. Therefore, it is undeniable that Maizuru Bay is facing depletion in clam resources.

B. Hidden Overexploitation

Whether past clam catch rates were performed appropriately from a standpoint of optimum clam stock management under an open access fishery is also investigated. It is assumed that the fishery can control the catch to maintain a constant clam stock, i.e., practice the sustainable usage of clam resources. This condition is given as $XM_k\big|_{t+1} = XM_k\big|_t$ in (30).

Fig. 11 compares the catch under a constant stock, the actual catch, and the estimated catch in the clam fishery. In fact, the precise clam stock is still unknown, but the 1980s' actual catch remained at approximately the same level as the catch under a constant stock condition. Therefore, it can be concluded that the clam fishery was sustainable in the 1980s.

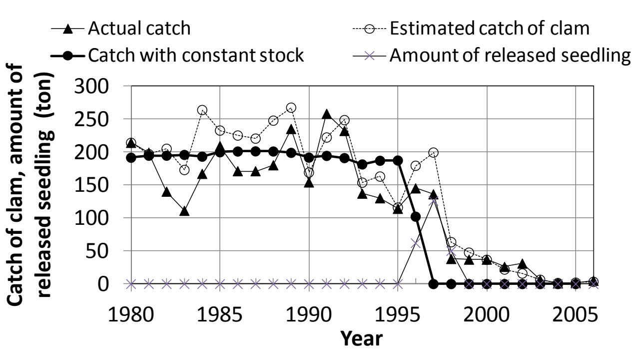

Fig. 11 Comparison of actual catch and catch under constant stock condition

It is pointed out that since the seedlings were released in 1996, both actual and estimated catch levels have constantly exceeded the catch level required to maintain the constant stock. Furthermore, considering the predator–prey system, the catch allowable under the constant clam resource condition becomes zero in the period 1997–2006. This indicates that the reduction rate in clams acting as prey of the predator exceeds the natural growth rate of clams. Furthermore, it is revealed that overexploitation in clams was hidden until 2006.

In contrast to the anticipation of clam growth by seedling release, the clam fishery could not guard against the feeding damage that most probably contributed to the clam stock reduction. Concurrently, the clam fishery would realize a large catch level immediately after the seedling release. The subsequent overexploitation continued until 2006, without any measures being taken to protect the clam resource.

Consequently, it is evident that the clam resource depletion was caused by both establishment of the predator–prey relationship after the seedling release and overexploitation. As a result, it can be concluded that the clam fishery has no other choice than to adopt a low labor input in response to the depression caused by the clam stock shortage in the predator–prey ecosystem.

VII. Conclusion

A two-country model was combined with a clam stock model and applied to the predator–prey ecosystem. An assumption that some predator mixed in with the clam seedling released in the bay could provide reasons for the depletion of clam resource and the current clam fishery depression.

This study can provide useful assistance by adopting policies and measures to exterminate predators, which is a significant step toward sustainable fishery development. When introducing policy variables relevant to economic measures and environmental technologies, the developed model will help perform a scenario analysis of resource recovery and sustainable development in the clam fishery. In addition, the developed model will also serve as a tool applicable to study other environmental resources and sustainable development in regional, national, and international levels.

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