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Assessment of fishery management by using a fishery simulator for bottom otter trawling in Ise Bay

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ABSTRACT

Improving the condition of coastal fishery requires the implementation of effective fishery management practices, as well as development of an assessment system. More efficient and sustainable fishing operations need to be determined considering both the resource and economic conditions. For the bottom trawling, fishery management considering only a single species might not be appropriate, because a wide variety of fish is caught by the trawling net. Thus in this study, we developed a fishery simulator for bottom otter trawling in Ise Bay, Japan, to treat two fish species—conger eel and mantis shrimp—which show distinct biological behaviors. The simulator was based on two models: a fish behavioral model that predicts the spatiotemporal variability of fish biomass and population size and a fishing operations model that predicts the fishing activities of trawling boats. The developed simulator could well reproduce the annual variations of catch per unit effort for conger eel and mantis shrimp. The model was also used to assess the effects of fishery management to control the use of fishing gear and boat number. The mesh size of trawling nets and the period for which these nets need to be used to maximize the total fish catch could be estimated based on the simulations. At the target ports, reduction of boat number could increase the profit because the effect of fixed cost change exceeded the impact of fish catch decrease; however, the optimum reduction rate was different across each port.

1. Introduction

Recently, coastal fishery in Japan is being seriously affected by situations such as decline of fishery resources due to environmental degradation or other reasons, problems in price determination and distribution structure, decrease of consumption, and unstable income of fishermen. The production of fisheries and aquaculture has dropped to less than half of its peak in 1984. The number of fishermen has also declined from 325,000 in 1993–167,000 in 2015. In addition, the ratio of fishermen older than 65, which was 18% in 1993, reached 36% in 2015 (Japan Fisheries Agency, 2016). Further, the wholesale price of landing area for fish has declined over recent years, since the development of large retailers such as supermarkets has changed the price determination for fishery products (Itakura, 2000). Moreover, the operation costs for fishing, such as fuel price, have been increasing (Hasegawa, 2008). Thus, the economic conditions of fishermen and fisheries cooperative associations have been adversely affected. Improving the condition of coastal fishery requires the implementation of effective fishery management practices, as well as development of an assessment system for the same. For example, more efficient and sustainable fishing operations need to be determined considering the resource and economic conditions.

A number of models considering both ecological and economic conditions have been developed and applied to assessing fishery management (e.g., Blenckner et al., 2011; Fulton et al., 2011; Kaplan and Leonard, 2012; Bastardie et al., 2014; Romagnoni et al., 2015; Russo et al., 2015). Especially, the inconsistency of single-species objectives in a mixed-fisheries context has been highlighted as a key issue through multi-species and multi-fleet modelling (Kraak et al., 2008; Pelletier et al., 2009; Andersen et al., 2012; Ulrich et al., 2012). However, there have been very few applications of bio-economic models to Japanese coastal fisheries. In the present study, trawl fishery in Ise Bay was selected as a target for analysis. Ise Bay is one of the typical semi-enclosed bays that are surrounded by large urban areas. Coastal development and terrestrial loads are reported to have caused environmental degradation and affected marine ecosystem and fisheries. In particular, oxygen-deficient water at the bottom layer in the summer season severely impacts the benthic ecosystem (Takahashi et al., 2000; Suzuki,

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2001; Fujiwara et al., 2002). However, the ratio of natural coasts is relatively higher in Ise Bay than in other urbanized enclosed bays such as Tokyo Bay and Osaka Bay, and fisheries activities are still continuing under harsh social conditions and decreased marine resources (Funakoshi, 2008; Ise Environmental Database, 2008).

Bottom otter trawling is one of the major fishery activities in Ise Bay; it is sensitive to marine environmental conditions such as dissolved oxygen level. The fish catch of bottom otter trawling in Ise Bay was about 7200 tons in 2000, but it dropped to about 4600 ton in 2009. The main target species are conger eel *Conger myriaster*, mantis shrimp *Oratosquilla oratoria*, Japanese pufferfish *Takifugu rubripes*, *Trachysalambria curvirostris*, and *Lateolabrax japonicus* (Japan Fisheries Agency, 2012).

We have been developing a fishery simulator for bottom trawl fishery in Ise Bay. Tabeta et al. (2012) investigated the actual status of bottom otter trawling in Ise Bay by collecting the fishing records by using the global positioning system (GPS) and developed a fishing operation model. Motomiya et al. (2015) reproduced the annual changes of spatiotemporal variations in conger eel distribution in Ise Bay by applying the fish behavioral model developed by Hakuta and Tabeta (2013). Tabeta et al. (2015) developed a simulator for conger eel fishery in Ise Bay; it is a combination of the fish behavioral model by Motomiya et al. (2015) and the fishing operation model by Tabeta et al. (2012). However, fishery management considering only a single species might not be appropriate for bottom trawling, because a wide variety of fish is caught using this method.

Therefore, in this study, the fishery simulator for bottom otter trawling was extended to treat two fish species—conger eel and mantis shrimp—which show distinct biological behaviors. The simulator is based on the fish behavioral model that predicts the spatiotemporal variability of fish biomass and population size and the fishing operations model that predicts the fishing activities of trawling boats. By using the developed simulator, we investigated the effects of fishery management, such as control of fishing gear and fishing effort.

2. Model

The fisheries simulator was based on two models—the fish behavioral model and the fishing operation model—as shown in Fig. 1.

2.1. Fish behavior

The fish behavioral model includes three sub-models of migration, growth, and population change (Hakuta and Tabeta, 2013; Motomiya et al., 2015).

In the migration sub-model, the direction of fish movement is determined by the preference intensity of environmental factors.

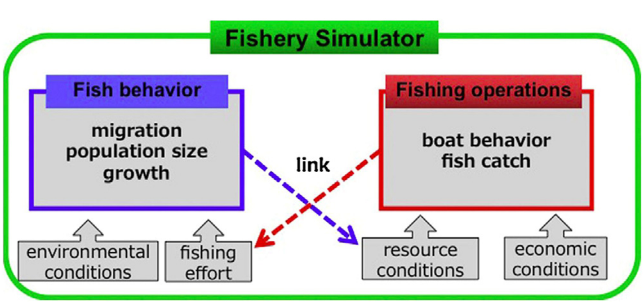

Fig. 1. A conceptual diagram of the fisheries simulator (Tabeta et al., 2015).

For each time step, the preference intensity is calculated using the following equation:

$$P^* = \prod_j^J P_j \quad (1)$$

where P^* is the inclusive preference intensity, which takes a value between 0 and 1, and J is the number of environmental factors. In the present study, water temperature, dissolved oxygen concentration, and benthic sediment were considered as environmental factors. The preference intensity for each environmental factor also takes the value between 0 and 1. For water temperature T_i at grid i, the preference intensity P_1 is determined as follows:

$$P_1 = \begin{cases} 0 & \text{if} T_i < T_{CL} \\ \dfrac{T_i - T_{CL}}{T_{OL} - T_{CL}} & \text{if} T_{CL} \le T_i < T_{OL} \\ 1 & \text{if} T_{OL} \le T_i < T_{OH} \\ 1 - \dfrac{T_i - T_{OH}}{T_{CH} - T_{OH}} & \text{if} T_{OH} \le T_i < T_{CH} \\ 0 & \text{if} T_i \ge T_{CH} \end{cases} \quad (2)$$

where T_{CL} (°C) is the lower temperature limit; T_{OL} (°C), the lower optimum temperature; T_{OH} (°C), the upper optimum temperature; and T_{CH} (°C), upper temperature limit. For the dissolved oxygen concentration, DO_i, the preference intensity P_2 is calculated as follows:

$$P_2 = \begin{cases} 0 & \text{if}\, DO_i < DO_c \\ \dfrac{DO_o - DO_i}{DO_o - DO_c} & \text{if}\, DO_c \le DO_i < DO_o \\ 1 & \text{if}\, DO_i \ge DO_o \end{cases} \quad (3)$$

where DO_C (mg/L) is the critical dissolved oxygen concentration and DO_O (mg/L) is the lower limit of the optimum dissolved oxygen concentration. The preference intensity of benthic sediment P_3 was also considered for mantis shrimp; this factor depends on the type of sediment.

The ratio of individuals r that can move during one time interval Δt depends on the swimming speed v of each fish species and grid size Δx as follows:

$$r = \frac{v\Delta t}{\Delta x} \quad (4)$$

Assuming the likelihood that the fish will stay or move is proportional to the preference intensities in the target grid and the adjacent ones, and the allocation rate D_i from the current grid i_0 to grid i is expressed as follows:

$$D_i = \begin{cases} \dfrac{rP_i^*}{\sum_{i_1}^{I_1} P_{i_1}^*} & (i \ne i_0) \\ \dfrac{rP_{i_0}^*}{\sum_{i_1}^{I_1} P_{i_1}^*} + (1-r) & (i = i_0) \end{cases} \quad (5)\quad(5)$$

where I_1 is the number of adjacent grids from grid i. The allocation ratio D_i can be used to express the temporal update of population number of age-y fish $N_{i,y}$ as follows:

$$N_{i,y}^{n+1} = \sum_{i_2}^{I_2} \left(N_{i_2,y}^n D_{i_2} \right) \quad (6)$$

In the growth sub-model, we used the following growth function (Pauly and Gaschutz, 1979) to calculate the average body length L_t at age t:

$$\boldsymbol{L_t = L_\infty} \left(1 - \boldsymbol{e}^{-\boldsymbol{K}_0(\boldsymbol{t}-\boldsymbol{t}_0) - \frac{\boldsymbol{K_S}}{2\pi} \sin 2\pi(\boldsymbol{t}-\boldsymbol{t_s})}\right) \quad (7)$$