Ecosystem Approach for Management of Artificial Release of Chum Salmon from Japan Based on a Bioenergetic Model Coupled with NEMURO

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Our goal is to estimate the optimum amount of artificial releases of chum salmon to maximize the income of chum salmon fishermen in Hokkaido, Japan, under the restriction of the carrying capacity of ocean habitat.

Income of fishermen

Income of fishermen can be calculated by multiplying total catch by unit price. The number of adult chum salmon that returned is calculated by multiplying the released number by the return ratio. The return ratio of released chum salmon from Hokkaido is between 2% and 6% (National Salmon Resources Center, NSRC). The number of released salmon is 3 billion (Okamoto 2009) and the mortality ratio is supposed to be constant, so in our model, the return ratio is fixed at 4%. Almost 90% of returning salmon is caught by set nets (NSRC). The total number of set nets is 886 in Hokkaido in 2008 (Statistics by Ministry of Agriculture, Forestry and Fisheries, Japan; available at www.maff.go.jp/j/tokei/kouhyou/kaimen_gyosei/). Consequently, the total catch by one set net (N) is calculated as follows:

$$N = 3*10^9*0.04 * 0.9/886 \quad (1)$$

The time-dependent features of a year class of Hokkaido chum salmon caught by set net is shown on the NSRC homepage (available at salmon.fra.affrc.go.jp/zousyoku/H22salmon/h22salmon.htm#4). In our model, the return ratio and year-class ratio is fixed. Averaging the year-class return ratio for ocean age-3 and -4 chum salmon leads to the ratio of 62.9 : 37.1 for age-3 and-4, which means N*0.629 is the number of age-3 fish and N*0.371 is the number of age-4 chum salmon returning to Hokkaido.

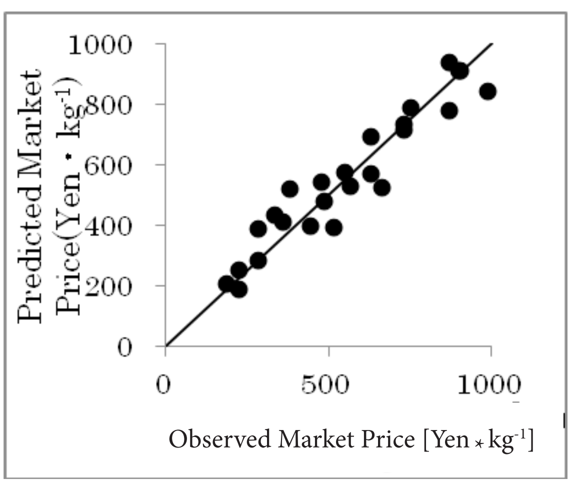

Fig. 1. Comparison between predicted and observed market price.

We can calculate the unit price of fish in the market (y) using multiple regression of the wet weight of ocean age-4 (x1) salmon and the return number (x2), as is shown in Figure 1 (r=0.92).

$$y = 0.499x_1 - 0.530x_2 \quad (2)$$

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The total income (IC) is calculated as follows:

$$IC = ((N*0.629*\text{wet weight of age-3 chum salmon}) + (N*0.371*\text{wet weight of age-4 chum salmon}))*y \quad (3)$$

According to data of the Japan Fisheries Research Agency, in 2006 the number of set nets in Hokkaido was 886. Consequently, the income per one set net is represented as IC/886.

Wet weight of chum salmon

Kishi et al. (2010) developed a bioenergetics model for chum salmon coupled with the results from a lower trophic ecosystem model embedded into a three-dimensional global model. In the bioenergetics model, respiration and consumption terms are assumed to be functions of water temperature and forage (zooplankton) density, which are the determining factors of body size. The detailed descriptions are provided in Kishi et al. (2010). Urawa (2000) suggested that inter-annual variations in wet weight of chum salmon can be observed after they migrate into the western North Pacific from the Okhotsk Sea. In our analysis, we excluded the juvenile period spent in the Okhotsk Sea and begin the simulation at age 404 days when the fish are in the western North Pacific. We used the daily averaged output (from Aita-Noguchi et al. 2003) for the upper 20 m of the water column and also averaged spatially within each box. In the Gulf of Alaska, chum salmon prefer jellyfish rather than copepods (Kaeriyama et al. 2004), and we assumed predatory zooplankton (ZP) to be the prey of chum salmon. In the NEMURO model, ZP includes jellyfish, salps, and/or krill (Kishi et al. 2007). The NEMURO describes zooplankton density as nitrogen density (mol N l^{-1}) that we converted into wet weight following Megrey et al. (2002). Chum salmon in the present model changes its prey based on Kishi et al. (2010). The NEMURO compartments of prey density ZP and ZL (non-predatory zooplankton) decrease by fish grazing. Chum salmon in the present model migrate from the northwestern Pacific to the Bering Sea and Gulf of Alaska following Kishi et al. (2010). The physical forcing of the NEMURO box model is given in the same way as Kishi et al. (2010).

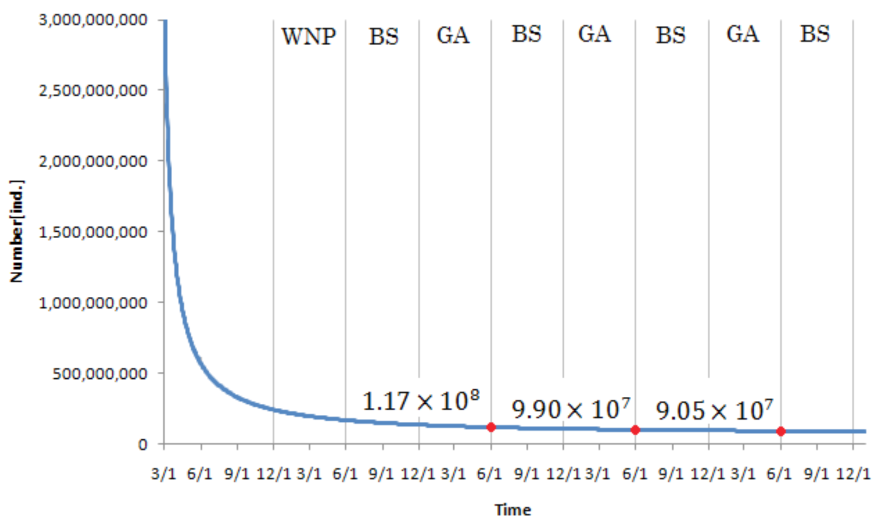

Fig. 2. The number of chum salmon through time when 3 billion fry are released. WNP: western North Pacific; BS: Bering Sea; GA: Gulf of Alaska.

Results in Figure 2 show the estimated number of chum salmon through time when 3 billion fry are released. The spatial volume where chum salmon live is estimated to be 4000 km^{-3} (200 km * 200 km * 100 m) for each area. Although this value is arbitrary, it is necessary for converting the number of salmon per m^{-3} that NEMURO requires for a predator. Figure 3 shows the time-dependent value of the calculated wet weight of Hokkaido chum salmon when 500 million, 1.0 billion and 1.5 billion fry are released (total number of chum salmon released in the North Pacific is 2, 3, and 4 billion, respectively). Differences in growth appears in ocean age-3 and -4. Body weight shrinks due to competition for food when the number released is 1 billion. Figure 4 shows the income of fishermen (per one set net) calculated by Eq. 2 and 3 and IC/886. The horizontal axis is the number of chum salmon released from Hokkaido. In 2007, the number released was 1 billion and Figure 4 suggests that the present number of releases brings about the maximum income to fishermen.

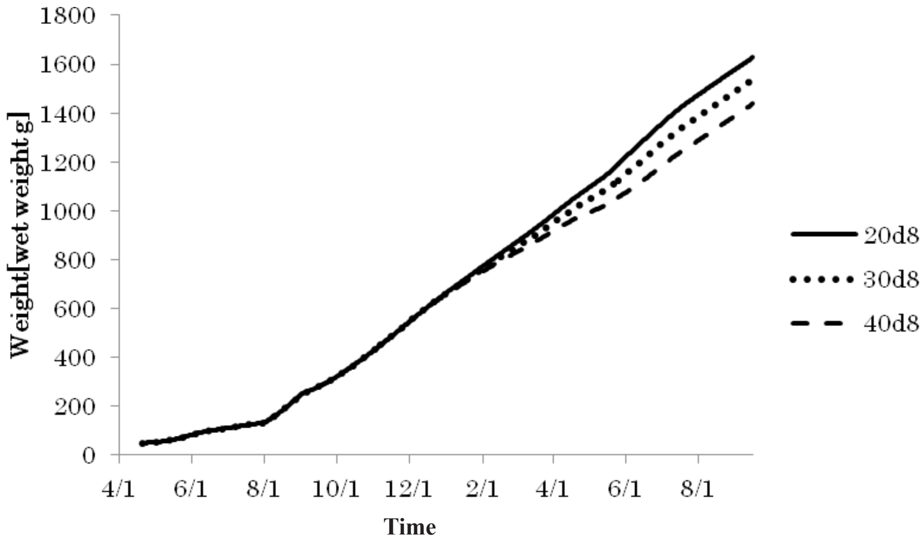

Fig. 3. Time-dependent value of calculated wet weight of Hokkaido chum salmon when 0.5 billion (black line), 1.0 billion (dotted line) and 1.5 billion (dashed line) fry are released (total number of chum salmon released in the North Pacific is 2 billion, 3 billion, and 4 billion, respectively).

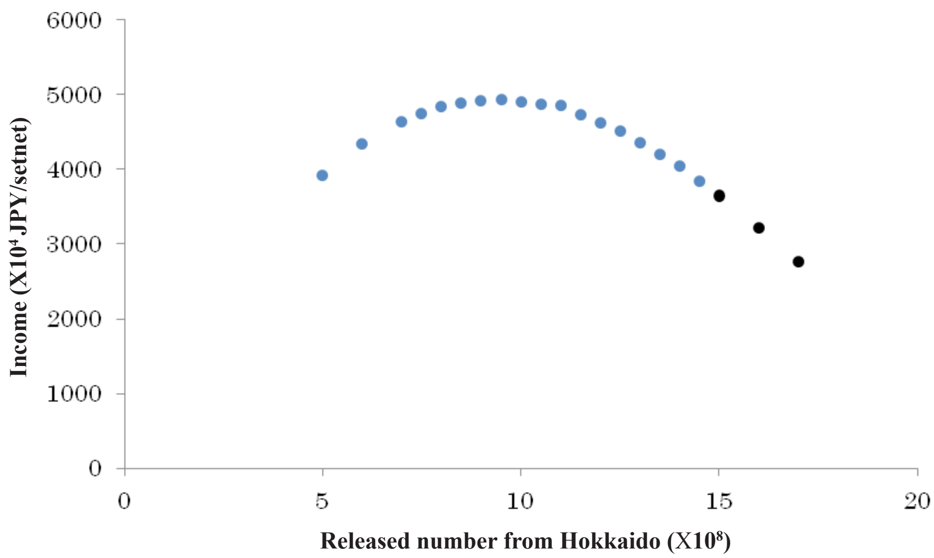

Fig. 4. Income to fishermen per one set net related to the number of Hokkaido chum salmon released.

In summary, the suitable release number of Hokkaido chum salmon was calculated based on an "ecosystem approach". The constraining condition is the carrying capacity of North Pacific Ocean, which is calculated by a two-way version of NEMURO, and the cost function, which is total income to fishermen. The unit price of chum salmon, which is used to calculate a cost function, is determined by empirical data as a function of return ratio. NEMURO, which is a lower trophic model of the North Pacific, coupled with a physical model was used to calculate prey density and to predict wet weight of salmon. Observations indicate a decline in the number of salmon. Results indicate that the present release number under current conditions brings about the maximum income to fishermen. The present model is based on the assumption that the return ratio is constant (4%), however, it must be related to the physical environment and release number. Competition for food among chum salmon and the other species is also not considered in the present model. We should include these aspects in future considerations.

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