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The importance of spawning season on the growth of Pacific saury: A model-based study using NEMURO.FISH

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ABSTRACT

NEMURO.FISH was applied to Pacific saury to study the dependence of spawning season on growth. The model was composed of three ocean domains, which corresponded to the Kuroshio, the Oyashio, and the interfrontal zone (mixed water) regions. In these three domains, a lower trophic model (NEMURO) was coupled with a simple physical model, and the time-variation of three zooplankton size classes was input as prey densities into the saury bioenergetics model. Three numerical experiments were examined using this model, which corresponded to three different spawning seasons. Results showed that in the first year winter-spawned saury showed the fastest growth, and spring-spawned showed the slowest growth, while in the second year (time to grow to 120 g wet weight), the reverse occurred, i.e., spring-spawned saury showed the fastest growth. This difference in growth, which depends on the spawning season, can explain the bimodal size distribution of early autumn catch data.

1. Introduction

Pacific saury (*Cololabis saira*) is an important pelagic commercial fish in the northwestern Pacific and the average total catch of saury is about 250,000 tonnes (t). Saury spawning starts in the mixed water region (the Kuroshio–Oyashio interfrontal zone) in autumn, moves to the Kuroshio region (the subtropical region) in winter and shifts back to the mixed water region in spring (Odate, 1977; Watanabe and Lo, 1989; Watanabe et al., 1997; Ito et al., 2004). Juveniles are advected to the Kuroshio extension region, then grow and migrate to the Oyashio region (the subarctic region) through the mixed water region for feeding. After sufficient feeding, they migrate back to the Kuroshio region to spawn. The knob length (KL, nearly the same as body length) of saury reaches 30 cm in adults and many studies have estimated the growth rate of saury using otolith analyses (Suyama et al., 1996; Oozeki and Watanabe, 2000). A recent fish bioenergetics model (Ito et al., 2004) used parameter sets derived from otolith analyses. They used a bioenergetics model coupled with a lower trophic model (NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography); Kishi et al., 2007) and analyzed the influence of climate change on the growth of Pacific saury. Their model was composed of three oceanic domains (hereafter called boxes) corresponding to the Kuroshio (KR), the Oyashio (OY), and the interfrontal zone (mixed water regions) (MW), and showed that the surface heating or cooling in MW has the most influence on the change in Pacific saury growth rate. Warming in

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MW results in a reduction of zooplankton density and slows the growth of saury. The effect of warming in OY shows the same effect on saury growth rate, whereas, warming in KR accelerates the loss of saury weight.

The life history of Pacific saury is complicated and it has been difficult to clearly identify the mechanisms that determine variations in biomass and size-composition. Recent work by Kurita et al. (2004) estimated the hatch date of large Pacific saury and, combined with the information of the growth of the saury with no hyaline zone (Okuda, 2002), built a new life history scenario. According to Kurita's new scenario, saury, which is born early (autumn and winter), spawn in the first winter and also in the second winter. However, later (spring) spawned saury do not spawn in the first year, but do spawn in the second year.

Oozeki et al. (2004) and Oozeki and Watanabe (2000) showed that sea surface temperature (SST) and food density affect larval growth during early stages and SST and chlorophyll become more important in later stages. But the environmental influences on young and adult saury have not been quantified because saury is very sensitive and difficult to rear in laboratories. Although the life span of Pacific saury is unclear, Kosaka (2000) showed that two peaks in the size distribution can be found in early-autumn catch-data (right hand side of Fig. 7) and that these two peaks might be proof that the Pacific saury life span is about 2 years, considering that each peak corresponds to one main spawning season per year. Suyama et al. (2006) also revealed that Pacific saury consists of only 2-year-classes and the large-sized group (<29.0 cm) is considered to almost correspond to the age 1 fish group, while the medium- (24.0–29.0 cm) and small-sized groups (20.0–24.0 cm) almost correspond to the age 0 fish group.

In this paper, we improved the NEMURO.FISH model of Ito et al. (2004) and applied the model to three different spawning seasons. Our goal was to use the model to reproduce a reasonable time dependent growth curve of Pacific saury, which depended on spawning season. We performed three numerical experiments using this coupled model to answer the following questions: how do differences in spawning season affect saury growth? and how are bi-modal size distributions of catch data formed?

2. The fish bioenergetics/ecosystem coupled model

The basic model of the fish bioenergetics/ecosystem coupled model is NEMURO.FISH (NEMURO For Including Saury and Herring; Megrey et al., 2007). The NEMURO.FISH model was applied to saury life-history characteristics follows the approach described by Ito et al. (2004). NEMURO was applied to a three-box ocean model, where each box represents the KR, the MW and the OY region, respectively. In each box, SST was provided as the surface boundary condition and the mixed layer temperature was defined by SST (Fig. 1). SST is the highest in late August and lowest in late February (Fig. 6c of Ito et al., 2004). Temperature at the bottom of the mixed layer (BLT) was set to be constant and was given as the bottom boundary condition defined from the data of the World Ocean Atlas (Antonov et al., 1998). Bottom boundary conditions for temperature and nutrients in NEMURO are given in Table 1. The thickness of the mixed layer is increased (decreased) when the SST is lower (higher) than BLT although the mixed layer thickness could not be less than 30 m. The exchange rate of NO_3 and $Si(OH)_4$ between the mixed layer and the bottom layer was changed as a function of stability defined by the difference in temperature between SST and BLT. NEMURO was driven by SST forcing and light intensity at the surface. Small (ZS), large (ZL) and predatory (ZP) zooplankton densities and seawater temperature derived from NEMURO were used to couple with the Pacific saury bioenergetics model. Parameters used in the saury version of NEMURO.FISH are basically the same reported in Ito et al. (2004) except for a_c (the intercept for C_{MAX}, maximum consumption rate) and b_c (the slope of the allometric mass function for consumption). The value a_c is changed from 0.6 (cf. Table 2 of Ito et al., 2004) to 0.54 and the value b_c is changed from −0.340 (cf. Table 2 of Ito et al., 2004) to −0.256 because these values gave more reasonable results compared to observed data.

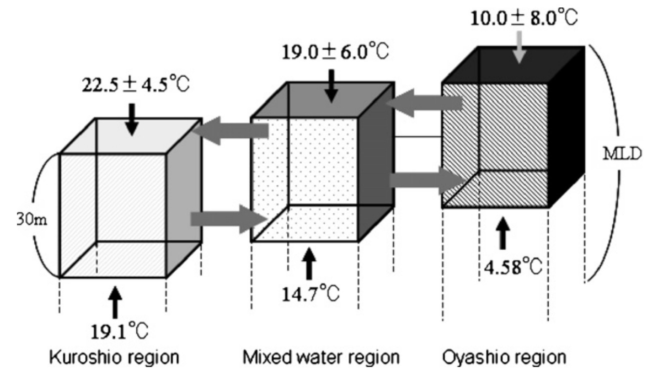

Fig. 1 – Schematic view of the three oceanographic domains. Each domain represents the Kuroshio, the mixed water and the Oyashio region, respectively. In each domain, SST is provided as the surface boundary condition (the numbers shown above each box are the annual mean and amplitude of SST) and the mixed layer temperature is defined by the SST. The temperature at the bottom of the mixed layer (the number shown beneath each box are the bottom temperature) is constant and given as the bottom boundary condition.

Table 1 – Bottom boundary conditions for temperature and nutrients in NEMURO

Bottom boundary condition	Kuroshio	Mixed water region	Oyashio
Water temperature (°C)	19.10	14.70	4.58
Nitrate (mol N l^{-1})	6.0×10^{-6}	18.0×10^{-6}	25.0×10^{-6}
Silicate (mol Si l^{-1})	6.0×10^{-6}	25.0×10^{-6}	30.0×10^{-6}

3. Material and methods

3.1. *Spawning season and area*

We divided the spawning season into three periods, autumn, winter and spring. In our model, the birth-date and spawning