Modeling the population dynamics of Pacific saury considering migration

Rentaro Mitsuyu and Toshihide Kitakado

Tokyo University of Marine Science and Technology, Japan.

ABSTRACT

The Pacific saury (*Cololabis saira*) is a commercially important small pelagic species distributed widely across the North Pacific, from the northern subtropical to the southern subarctic regions. In winter, it stays in the southern part of its range. From spring to summer, it migrates northward for feeding. In autumn and winter, it moves southward again and starts spawning during this migration. This species is currently managed by the North Pacific Fisheries Commission (NPFC), and its stock assessments are conducted using a Bayesian State-Space Production Model (BSSPM), which is non-spatial and does not account for migratory behavior. These assessments have indicated that the stock level has been low in recent years. In this study, we first constructed hypothetical stock dynamics for Pacific saury, based on the assumption that sea surface temperature (SST) significantly influences its migratory behavior. Using the constructed dynamics model, we generated synthetic catch-per-unit-effort (CPUE) data. We then attempted to reconstruct the original spatio-temporal stock distribution using the simulated CPUE and SST data. The reconstruction was successful, demonstrating the potential to estimate spatiotemporal changes in Pacific saury distribution based on CPUE and SST, given appropriate assumptions and sufficient data availability. Although further development is needed, our study framework would potentially contribute to (1) improving stock assessment and fisheries management under recent changes in the marine environment, (2) evaluating spatio-temporal management measures such as seasonal and area closures through Management Strategy Evaluation (MSE), and (3) integrating biological information revealed by otolith analysis and other techniques into population models.

1. INTRODUCTION

Background

- Pacific saury migrate annually, and their distributions in feeding and spawning areas are considered to be associated with growth and reproduction, respectively.
- These aspects are not considered in current stock assessments.
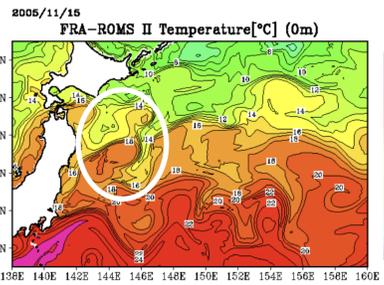

Fig. Pacific saury

Fig. Local oceanographic structures
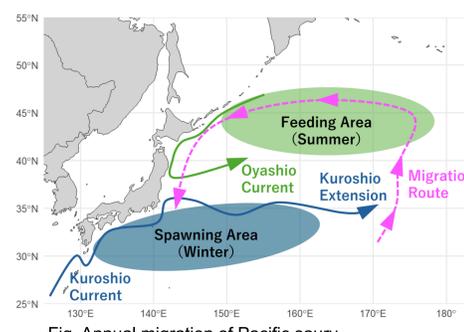(Branch of the Oyashio Current)

Fig. Annual migration of Pacific saury

Problem

- Considering the spatial distribution of Pacific saury may lead to more accurate stock assessments.
- However, fishing activities are limited to certain feeding areas, resulting in insufficient data coverage for conventional models that only consider spatial distribution.

A distribution model that explicitly incorporates migratory structure is required.

Objective

- Build a spatio-temporal model which explicitly incorporate the relationship between their migratory behavior and oceanic condition.
- Evaluate the model through the simple simulations.

2. METHODOLOGY

Model

$$B_{t+1} = \begin{bmatrix} B_{1,1,t+1} & \cdots & B_{1,m,t+1} \\ \vdots & \ddots & \vdots \\ B_{n,1,t+1} & \cdots & B_{n,m,t+1} \end{bmatrix} = \sum_{i=1}^{n} \sum_{j=1}^{m} (B_{i,j,t} - C_{i,j,t}) \times H_{i,j,t}$$

i: the i-th row (latitude)
j: the j-th column (longitude)

$B_{i,j,t}$: biomass at cell (i,j) and time t
$C_{i,j,t}$: catch at cell (i,j) and time t
$H_{i,j,t}$: migration matrix at cell (i,j) and time t

How to make migration matrix ($H_{i,j,t}$)

$\beta_1, \ldots, \beta_9$ are defined as:

$\beta_1' = \exp(\delta T_{i-1,j-1,t}^{20})$ $\beta_2' = \exp(\delta T_{i-1,j,t}^{20})$ $\beta_3' = \exp(\delta T_{i-1,j+1,t}^{20})$

$\beta_4' = \exp(\delta T_{i,j-1,t}^{20} + \eta^{west})$ $\beta_5' = \exp(\delta T_{i,j,t}^{20} - \delta' T_{i,j,t}^{10})$ $\beta_6' = \exp(\delta T_{i,j+1,t}^{20})$

$\beta_7' = \exp(\delta T_{i+1,j-1,t}^{20})$ $\beta_8' = \exp(\delta T_{i+1,j,t}^{20})$ $\beta_9' = \exp(\delta T_{i+1,j+1,t}^{20})$

δ: parameter
δ': parameter
η^{west}: westward migration effect $(\eta^{west} = 1)$

T^{20}: area proportion where SST < 20℃
T^{10}: area proportion where SST < 10℃

(Watanabe et al., 2006)

$\beta_j = \dfrac{\beta_j'}{\sum_{k=1}^{9} \beta_k'}$

$X = (x_1, \ldots, x_9) \sim Dir(\phi\beta_1, \ldots, \phi\beta_9)$

Here, $E[X_k] = \beta_k, \ Var[X_k] = \dfrac{\beta_k(1-\beta_k)}{1+\phi}$

$\beta_1', \ldots, \beta_9'$ represent habitat suitability scores the central cell and its eight neighboring cells. The movement probabilities β_j are obtained by normalizing these scores. For example, β_1 is the expected probability of moving to the northeast cell, and β_5 is the expected probability of staying in the central cell. And, ϕ controls the process variability.

$X_{mat} = \begin{bmatrix} x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 \\ x_7 & x_8 & x_9 \end{bmatrix}$ $H_{i,j,t}$ is the $n \times m$ matrix
for which $H_{i,j,t}[i-1:i+1, j-1:j+1] = X_{mat}$, otherwise 0.

$\log(CPUE_{i,j,t}) \sim N(\log(qB_{i,j,t}), \sigma^2)$

Estimation was conducted by MLE using the Laplace approximation and by a Bayesian method using MCMC.

Validation Experiment

Model validation was conducted as illustrated in the Conceptual Workflow, using a **5×5 spatial grid** and **10 time steps** (i=1–5, j=1–5, t=1–10).

1. CPUE and Catch data were simulated using the following parameter settings and artificial SST data.
2. Then, **CPUE**, **Catch**, and **SST** data were provided to the estimation model.
3. Parameter estimation was performed on **10 simulated datasets** under both the Laplace approximation and MCMC approaches, and results were compared.
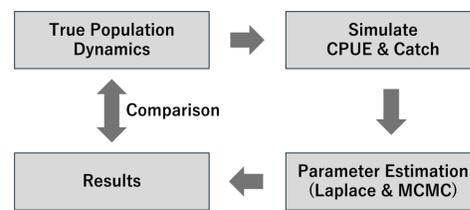

Fig. Conceptual Workflow

Parameter settings

δ	1
δ'	0.5
q	0.05
σ	0.05
ϕ	100
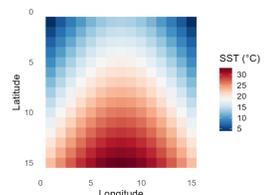
Fig. Sea Surface Temperature
(t = 1/10)

3. RESULTS

Estimated Biomass (Dataset1, t = 10/10)

True Biomass   Estimated Biomass (Laplace)   Estimated Biomass (MCMC)
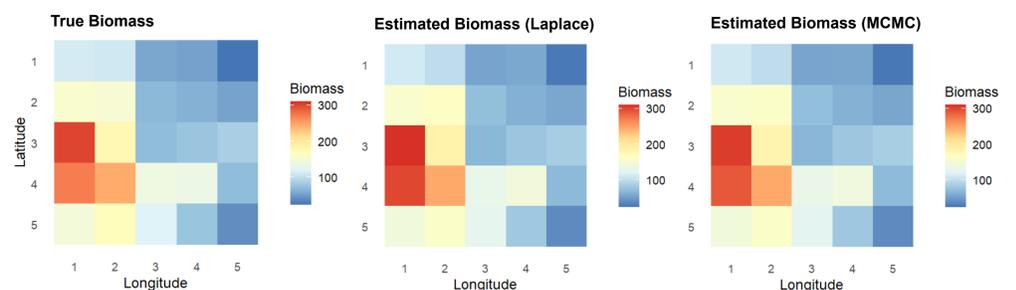
Estimated parameters
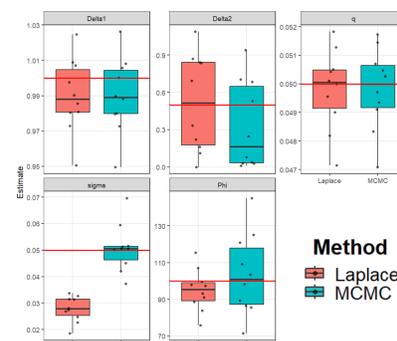
Note: MCMC uses the posterior median.
The red line indicates the true value.

- Both methods successfully reproduced the population dynamics.
- In both methods, estimation of key parameters related to migration (δ,δ') and observation (q) was satisfactory.

4. DISCUSSION & FUTURE WORKS

Summary

- Developed a state-space spatio-temporal model linking migration to oceanic environmental variables.
- Although the simulation was simple, the model successfully estimated the true biomass in each area.

Future works

- Evaluate model performance under more realistic scenarios (e.g., limited data availability, misspecified migration functions, or strong movement constraints imposed by oceanographic structures).
- Compare predictive performance with conventional distribution models.
- Explore potential applications for stock assessment.
- Further improve computational efficiency.

5. Key Reference

Watanabe, K., Tanaka, E., Yamada, S., & Kitakado, T. (2006). Spatial and Temporal Migration Modeling for Stock of Pacific saury Cololabis Saira (Brevoort), Incorporating Effect of Sea Surface Temperature. Fisheries Science, 72(6), 1153-1165.