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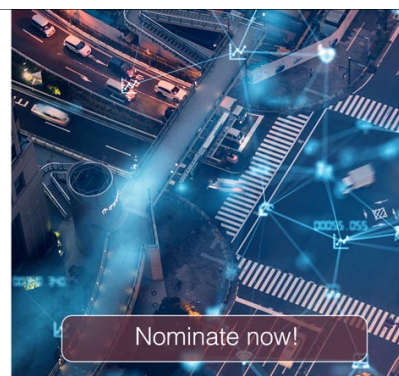


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Detection of potential fishing zone for Pacific saury (*Cololabis saira*) using generalized additive model and remotely sensed data

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Abstract. To evaluate the effects of oceanographic conditions on the formation of the potential fishing zones for Pacific saury in western North Pacific, fishing locations of Pacific saury from Defense Meteorological Satellite Program/Operating Linescan System (DMSP/OLS) and satellite-based oceanographic information were used to construct species habitat models. A 2-level slicing method was used to identify the bright regions as actual fishing areas from OLS images, collected during the peak fishing season of Pacific saury in the North Pacific. Statistical metrics, including the significance of model terms, and reduction in the Akaike's Information Criterion (AIC) were used as the bases for model selection. The selected model was then used to visualize the basin scale distributions of the Pacific saury habitat. The predicted potential fishing zones exhibited spatial correspondence with the fishing locations. The results from generalized additive model revealed that the Pacific saury habitat selection was significantly influenced by the SST ranges from 13-18°C, SSC ranges from 0.5-1.8 mg.m⁻³, SSHA ranges from 5-17 cm and EKE ranges from 700-1200 cm²s⁻². Moreover, among the set of oceanographic factors examined, SST explained the smallest AIC and is thus, considered to be the most significant variable in the geographic distribution of Pacific saury.

1. Introduction

Pacific saury (*Cololabis saira*) is one of the most commercially important fisheries, widely distributed in the North Pacific. It undergoes a seasonal migration, moving towards the northern waters of Japan in spring, staying in Oyashio region in summer, and migrating down south from autumn to winter season [1, 2]. Pacific saury was caught at night from August through December, with October as the peak fishing season [3]. Pacific saury is mostly found in the Oyashio areas, along oceanic fronts between Oyashio cold water and warm water from Kuroshio warm-core rings and Tsugaru warm waters [4, 5]. Therefore, oceanographic conditions are believed to largely influence its spatial distribution.

Due to high fluctuations in catches of Pacific saury [2, 6], prediction of potential fishing zones (PFZ) is essential to support fishery operations. Some models have been used to predict abundance and migration of Pacific saury, using single factor such as sea surface temperature [7-9]. However, we believed that the migration and distribution of Pacific saury could be potentially affected by other oceanographic factors. Therefore, this paper further explores a multi-parameter generalized additive



model (GAM) to predict the potential fishing zones for Pacific saury and evaluates the effects of oceanographic conditions on its preferred habitat in the western North Pacific.

2. Material and methods

2.1. Study area and satellite-based data

This study was conducted in the western North Pacific (140°-150°E and 34°-46°N), a region where Pacific saury fishing vessels operate off the east coasts of Japan (figure. 1). This area is also influenced by dominant physical features such as the Oyashio Current, Kuroshio Current, eddies, and fronts [10, 11]. The presence of these oceanographic features creates an interesting region to study the relationships between oceanographic conditions and various fisheries resources.

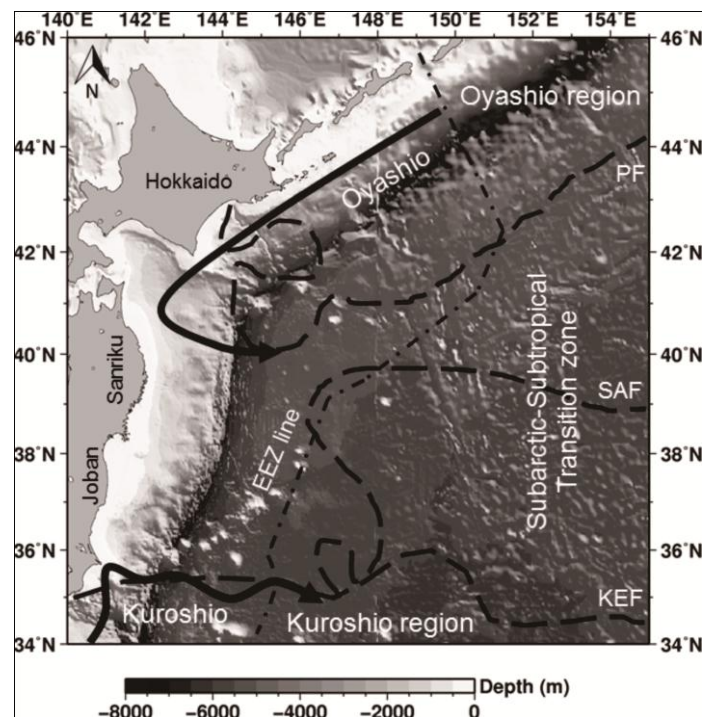


Figure 1. Study area in the western North Pacific (Redrawn from [3])

Fishing locations of Pacific saury, which are also assumed as the species occurrence points, were obtained from OLS nighttime images and were downloaded from the Satellite Image Database System of the Agriculture, Forestry and Fisheries Research Information Center of Japan Ministry of Agriculture, Forestry and Fisheries. We used the TeraScan system to analyze these images and process the nighttime lights into digital numbers within the range of 0-63. In addition, we utilized a 2-level slicing method [12] to detect fishing vessels. Since Pacific saury prefers cold areas as migration routes [4], SST was used to distinguish between the lights of vessels targeting Pacific saury and those of other fishing vessels [13].

The satellite-derived data of SST, SSC, EKE and SSHA from 2005 to 2013 were used as independent variables in GAMs. Daily SST and SSC were downloaded from NASA Goddard Space Flight Center (<http://oceancolor.gsfc.nasa.gov/cms/data/aqua>). We used the SeaDAS software to process these data and create maps with a 1-km resolution. The daily SSHA and geostrophic velocities (u , v) data from the Topex/Poseidon and ERS-1/2 altimeter were obtained from the Archiving Validation and Interpretation of Satellite Oceanographic Data (AVISO; <http://www.aviso.oceanobs.com>). The EKE was computed using the surface geostrophic velocities [14].

The monthly averages for each environmental variable from daily data sets were calculated with the grid function of the generic mapping tools (GMT 4.5.7) software. All the environmental variables were resampled to 1-km resolution prior to habitat model construction.

2.2. Generalized additive model

In this study, GAMs were constructed in R software (version 3.0.1) using the *gam* function of the *mgcv* package [15], with the Pacific saury presence as response variable and SSC, SST, EKE and SSHA as predictors. A model equation was given as follows:

$$g(u_i) = \alpha_o + s_1(x_{1i}) + s_2(x_{2i}) + s_3(x_{3i}) + \dots + s_n(x_{ni}) \quad (1)$$

where g is the link function, u_i is the expected value of dependent variable (presence or absence), α_o is the model constant, and s_n is a smoothing function with respect to the individual model covariates x_n .

Constructed GAMs can predict Pacific saury habitat suitability index (HSI) when a set of covariates used to build the model are provided. We constructed 15 models for the period between 2005 and 2010 and selected the best model based on Akaike's information criterion (AICs). The distribution of the GAM-predicted Pacific saury habitat were then compared with the monthly DMSP/OLS data.

3. Results and Discussion

We estimated distributions of Pacific saury in the study area, assuming that they were caught in areas where the fishing vessels were identified. Here, we focused on understanding the distributions of Pacific saury in October, corresponding to its peak fishing season [3].

Table 1 showed the statistical results for each of the 15 models earlier constructed using different oceanographic parameter combinations. Based on these results, all the predictor variables were highly significant ($p < 0.01$). However, the single parameter models exhibited the lowest explained deviance for EKE and SSHA. Among the single parameter models, SST had the highest explained deviance followed by SSC. The deviance explained and AIC values varied, as predictor variables were added to subsequent models. For instance, a model constructed from EKE and SSHA showed the lowest explained deviance. However, a combination of two-parameter models (SST and SSHA or SST and SSC) recorded relatively higher and lower values for deviance explained and AIC, respectively. The combination of SSC, SST and SSHA showed that all predictor variables were highly significant. Overall, the four-parameter model was selected as the best model, with highest cumulative deviance explained (CDE) and lowest AIC values.

Individual effect of each predictor variable was shown in GAM plots (figure 2). The model results indicated that the favorable habitat for Pacific saury was within the SSC range from 0.5 to 1.8 $\text{mg} \cdot \text{m}^{-3}$; SST from 14 to 16.5°C; EKE from 0 to 180 $\text{cm}^2 \cdot \text{s}^{-2}$ and less than 700 $\text{cm}^2 \cdot \text{s}^{-2}$; SSHA less than -7 cm and from 5 to 16 cm. [6] reported that SST has high relation with medium and large-sized of Pacific saury. In addition, [16] pointed out the SST preference for Pacific saury in October is 15 to 16°C. Together with SST, SSC affects the growth, distribution and migration pattern of Pacific saury [17, 18]. To describe PFZ in relation to mesoscale oceanography variability, SSHA and EKE were used. Our results indicate that fishing activities occurred in areas with low both EKE and SSHA, reflecting the likely association of this species with eddies. [19] reported that eddies create good feeding opportunities through local enhancement of SSC and zooplankton abundance and through the aggregation of prey organisms.

Table 1. Results from presence-only GAMs developed for Pacific saury using multiple oceanographic factors. The best model was selected based on reduction of AIC and increase in CDE.

| Model | Variable | <i>p</i> -value | AIC | CDE (%) |
|------------------------------|---------------------------|----------------------------------------------------------------------------------------------------------------------|----------|---------|
| SSC | SSC | $<2.00 \times 10^{-16}***$ | 58410.9 | 13.4 |
| SST | SST | $<2.00 \times 10^{-16}***$ | 47550.55 | 29.5 |
| SSHA | SSHA | $<2.00 \times 10^{-16}***$ | 60237.73 | 10.7 |
| EKE | EKE | $<2.00 \times 10^{-16}***$ | 61631.4 | 8.62 |
| SSC + SST | SSC SST | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 46333.72 | 31.3 |
| SSC + SSHA | SSC SSHA | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 55251.17 | 18.1 |
| SSC+ EKE | SSC EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 56609.64 | 16.1 |
| SST+ SSHA | SST SSHA | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 45328.34 | 32.8 |
| SST+ EKE | SST EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 46465.89 | 31.1 |
| SSHA+ EKE | SSHA EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 57672.22 | 14.5 |
| SSC+ SST+ SSHA | SSC SST SSHA | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 44014.9 | 34.8 |
| SSC+ SST+ EKE | SSC SST EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 45046.54 | 33.3 |
| SST+ SSHA+ EKE | SST SSHA EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 44551.71 | 34 |
| SSC+ SST+ SSHA+ EKE | SSC SST SSHA EKE | $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ $<2.00 \times 10^{-16}***$ | 43021.93 | 36.3 |

*** indicates statistical significance at the 0.001 level

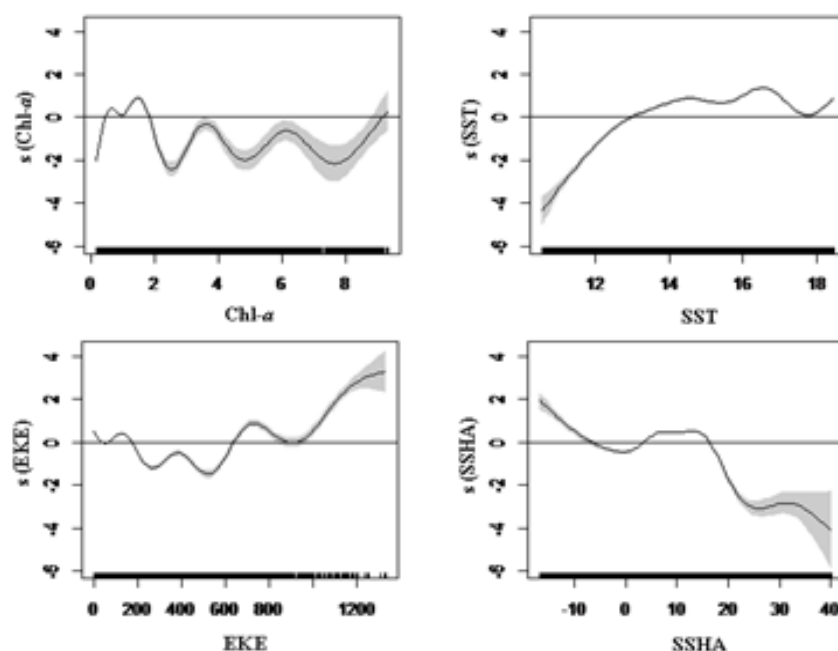


Figure 2. Effects of the 4 environmental variables –SSC, SST, EKE, SSHA, on Pacific saury presence derived from GAM for August 2005–2010. The x-axis shows the value of the explanatory variable, and the y-axis shows the contribution of the smoother to the fitted values. The tick marks on the horizontal axis represent the values of the observed data points; the thick line indicates the fitted function. Grey-shaded area represents the 95% confidence intervals. The horizontal line at zero indicates no effect. The percent of occurrence was higher for all values, for which the fitted GAM function was above the zero axis and lower for values less than 0.

3.1. Prediction and validation

Figure 3 showed the predicted HSI overlaid with actual presence of Pacific saury. During October, most of the fishing points appeared southeast Hokkaido and east of Sanriku (39°–42°N). The presence of fishing locations derived from the OLS images showed high especially in 2005–2007. Based on the predicted HSI maps, the probability of occurrence of Pacific saury in the east and southeast of Hokkaido and south of the Kuril Islands was high. Similarly, the results showed that high probability of occurrence were also found off the Kuroshio-Oyashio transition zone (40°N).

In October, most of the Pacific saury fishing vessels were located around the east coasts of Hokkaido and Sanriku. It has been believed that the observed southward movement was potentially driven by the southward extension of the Oyashio fronts [8, 16] and these features served as the preferred migratory routes of marine species including Pacific saury [4, 20]. In general, the predicted distributions of Pacific saury during October revealed areas of high probability of occurrence southeast off Hokkaido and east of Sanriku. The distribution and migration of Pacific saury in western North Pacific, during the fishing season from August to December, were explained in detail by [3].

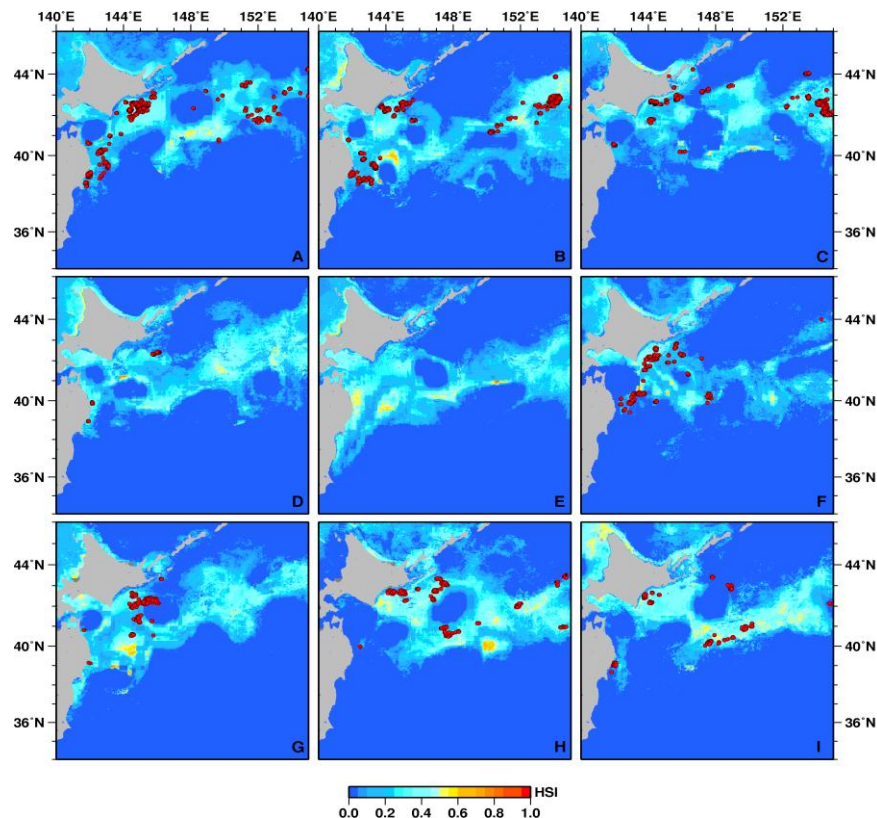


Figure 3. The spatial distributions of potential fishing locations of Pacific saury from DMSP/OLS (red dots) for (A) October 2005 to (I) 2013 overlain on habitat suitability maps. The suitability is depicted as the habitat suitability index (HSI) with values ranging from 0 to 1, representing "poor" to "good" habitat quality, respectively.

Among the set of oceanographic variables examined, SST showed the highest model contribution, thereby suggesting the sensitivity of Pacific saury distribution to temperature changes. For instance, increase in temperature could prevent or delay the southward migration of Pacific saury in winter [21]. The winter SST changes in Kuroshio–Oyashio Transition Zone and Kuroshio and Oyashio regions were also shown to impact the abundances of the large-sized (winter cohort) and medium-sized (spring cohort) groups of Pacific saury [6].

4. Conclusions

Pacific saury potential fishing zones mostly occurred around the east coast of Hokkaido and Sanriku in October. Generative additive models have shown the capability to predict the potential fishing zones for Pacific saury in the western North Pacific.

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