学位論文内容の要旨

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学 位 論 文 題 目

Spatial modeling of Pacific saury (*Cololabis saira*) potential fishing zones
in the western North Pacific using remotely sensed data

リモートセンシングを用いた西部北太平洋におけるサンマの潜在的漁場の空間モデリング

1. Introduction

Pacific saury (*Cololabis saira*) is widely distributed in the western North Pacific from subarctic to subtropical waters and is also one of the commercially important pelagic species not only in Japan but also in Russia, Korea and Taiwan. Most studies of Pacific saury distribution and migration have used in situ or log book data as well as models to investigate growth and abundance. However, no studies have integrated high resolution nighttime satellite images with habitat modeling to investigate the potential fishing zone of Pacific saury. The fishing boats equipped with lights, such as Pacific saury fishing boats, can be identified by night light images generated by the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) sensor.

The abundance, size and location of Pacific saury fishing grounds are largely affected by oceanographic conditions. Therefore, for sustainable management of Pacific saury resources in the western North Pacific, understanding the effect of environmental factors on catch distribution is essential. The ultimate goal of this study was to investigate how Pacific saury fishing ground and migration both temporally and spatially affected by oceanographic condition in the western North Pacific.

2. Material and methods

This study was conducted in the western North Pacific, extending from 140° to 155°E and from 34° to 46°N. This study utilized DMSP/OLS data, remotely sensed data, and reanalysis data from the 3-dimensional multi-variate ocean variation estimation system for the western North Pacific (MOVE-WNP). Remotely-sensed data derived environmental variables included chlorophyll-*a* (Chl-*a*) and sea surface temperature (SST) (MODIS-Aqua), sea surface height anomaly (SSHA) and eddy kinetic energy (EKE) (AVISO). The DMSP/OLS data and satellite remotely sensed data were analyzed for 9 years data set from August through December during 2005-2013. The period from August to December was chosen for analyses as it corresponds to the fishing season of Pacific saury in Japan. The fishing areas were defined as the bright areas created by 2-level slicing methods. We used SST to distinguish between the light of Pacific saury fishing fleets and other fishing fleet lights since Pacific saury preferred colder areas for their migration routes. Further analysis was undertaken with a generalized additive model (GAM), maximum entropy (Maxent) model. Moreover, others habitat model algorithm available from BIOMOD2 package such as Generalized Linear Model (GLM) and Multiple Adaptive Regression Splines (MARS), Artificial Neural Network (ANN), Surface Range Envelop (SRE) or usually called BIOCLIM and Flexible Discriminant Analysis (FDA) were also implemented in R software (version 3.3.3k) to examine the relationship between oceanographic conditions and distribution of Pacific saury. In an attempt to estimate the impact of global warming under different emission scenarios, habitat was re-modelled by changing only one eceanographic factor (SST). We used future SST projections under Representative Concentration Pathway (RCP) 4.5 in CMIP5 to understand the impact of global warming on the potential fishing zone of Pacific saury.

3. Results and discussion

The DMSP/OLS nighttime visible images were used to locate fishing vessel lights across space and time and assumed that Pacific saury was caught in areas where fishing vessels were identified. Based on the derived fishing vessel locations, we were able to estimate the spatial and temporal distribution of Pacific saury potential fishing zones.

At the beginning of fishing season (August through September), DMSP/OLS derived fishing locations showed that most of Pacific saury vessels appeared east of the Hokkaido and south of Four Island. In the middle of the fishing season (October through November), Pacific saury fishing vessels slightly moved to the south and appeared mostly around the eastern coasts of Hokkaido and Sanriku, potentially resulting from southward extension of Oyashio fronts. At the end of fishing season (December), Pacific saury vessels concentrate in Sanriku and Joban coasts. These results were in agreement with the report of the major fishing season and migration of Pacific saury.

DMSP/OLS images also showed that some of the fishing vessels appeared outside of the exclusive economic zone of Japan, possibly because Pacific saury is an oceanic spawner unlike other small pelagic fishes such as Japanese sardines and Japanese anchovy that generally spawn in the coastal and nearshore waters around Japan. A report showed the low capture of fish west of 150^{o}E from June to July during the pre-fishing season, indicates that Pacific saury caught by Japanese fishing vessels were located far from the northeastern coasts of Japan.

The predicted distribution of Pacific saury in the western North Pacific revealed areas of high probability of occurrence off Hokkaido and the Four Islands, areas that gradually moved south toward the Sanriku and Joban coasts by the end of the fishing season. These patterns coincided with the north–south migration of Pacific saury that marks the start and end of the fishing season. Results from the modeling approach further indicate that the highest probability of presence occurred along the Kuroshio–Oyashio transition zone in November.

The occurrence of large-sized Pacific saury off the southern Four Islands during their spawning migration indicates that a high proportion of large-sized Pacific saury moved from the high seas to coastal waters at the beginning of their migration toward the southwest-movement that was then followed by a similar migration of medium-sized Pacific saury. Therefore, abundance of Pacific saury off the coastal waters in our study is higher relative to the abundance observed in regions in the high seas. The high presence of Pacific saury at the coasts also could be a result of the westward current intensification, which can result in the formation of oceanic fronts. These frontal features have been known as the preferred migratory routes of Pacific saury and other marine species.

Although oceanographic conditions are likely to affect species distribution, other factors, such as prey density, are equally important. In the Kuroshio–Oyashio transition zone, Oyashio intrusions transport organic matter, thereby supporting the production of copepods, which are the primary prey of Pacific saury. This salient physical process could potentially explain the existence of habitat areas of Pacific saury in the transition zone, and consequently highlight the importance of this region as migratory and feeding corridors for Pacific saury.

For all models, the predictive performance was evaluated based on Cohen’s kappa, true skill statistics and area under the curve (AUC) of receiver operating characteristic. All monthly models significantly fitted better than they were fitted by chance as supported by the modest values of the performance metric (AUC>0.5). However, a kind of machine-learning model (i.e., Maxent) shows better performance relative to conventional regression-based algorithms. In our study, SST (among the set of oceanographic variables examined) showed the highest contribution to all monthly base models, indicating the sensitivity of Pacific saury to temperature changes. These results in agreement with other researchers who reported the effect of temperature changes in growth, abundance and migration of Pacific saury.

To our knowledge, this study was the first attempt to use both EKE and SSHA to describe the potential Pacific saury fishing habitat in relation to mesoscale oceanography variability. The results indicate fishing activities occurred in areas with low to moderate EKE, reflecting the likely association of this species with eddies. Eddies are likely trap prey of Pacific saury, creating good feeding opportunities through local enhancement of Chl-*a* and zooplankton abundance and through the aggregation of prey organisms. In the same manner, higher contribution of Chl-*a* in September can be explained by the importance of forage to Pacific saury where together with SST, Chl-*a* influences Pacific saury growth, recruitment, distribution and migratory patterns.

In an attempt to estimate the impact of global warming under different emission scenarios, habitat was re-modelled by changing only one eceanographic factor (SST). The results showed acceptable assessment of how Pacific saury potential fishing zone might change under different warming scenarios. The latitudinal displacements of the poleward shift increased from the 2025 to 2100 scenarios. The largest latitudinal displacements from the recent years would be recognized for the 2100.

Finally, DMSP/OLS nighttime images were shown useful in investigating the fishing lights distribution. However, cloud contamination posed a significant limitation on the use of DMSP/OLS images and reduced the density of proxy fishing locations thus, log-book data are needed to confirm the validity of fish occurrences in the future. Moreover, the integration of these empirical data with multi sensor remote sensing information within a modeling platform could offer a powerful and innovative way to identify the potential fishing zones for Pacific saury and could be used to support fisheries management decisions.