博　士（水産科学）　ムゴ　ロビンソン　モゲンディ

学 位 論 文 題 名

Spatial Modeling of Skipjack tuna (*Katsuwonus pelamis*) Habitat in the western North Pacific using Satellite Remote Sensing and GIS

（衛星リモートセンシングと GIS（地理情報システム）を用いた
西部北太平洋におけるカツオ生息域の空間モデリング）

学位論文内容の要旨

1.0 Introduction

Skipjack tuna (*Katsuwonus pelamis*) is a highly migratory pelagic species inhabiting all tropical and sub-tropical waters of the world oceans. It is one of the most commercially important species of tuna, otherwise referred to as "principal market species" (others include yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), albacore (*Thunnus alalunga*) and bluefin (*Thunnus thynnus*) tunas). By species skipjack tuna accounts for the greatest proportion of world catches. Prudent management of such a species is beneficial to humanity and applied research using satellite remote sensing and Geographical Information Systems (GIS) can help to generate information relevant for management. Recently, application of oceanographic satellite remotely sensed data in pelagic fisheries has emphasized identification of potential fishing zones (PFZ) and search for pelagic fishery management strategies underpinned by scientific findings. Building on such a background, I hypothesized that it was feasible to (a) derive habitat signatures of skipjack tuna from satellite remotely sensed information, (b) test the potential impact of global warming on the habitats and (c) assess ecological interactions using remote sensing approaches. Consequently, the objectives of this work were (i) to study skipjack tuna habitat from multi-sensor satellite remotely sensed environment and fishery data, using generalized additive models (GAMs) and GIS; (ii) to determine habitat suitability indices (HSI) for skipjack tuna using remotely sensed data and Ecological Niche Factor Analysis (ENFA) models and subsequently assess the potential impact of global warming (using SST forcing) on the habitat; and (iii) to assess possible ecological interactions between skipjack tuna, pacific saury and squids using maximum entropy (MaxEnt) models.

2.0 Materials and Methods

This work was conducted in the western North Pacific (WNP), the area bound by 18-50°

N and 125-180° E. The physical oceanography of the WNP is largely shaped by three main currents, the Oyashio Current, the Kuroshio Current, and the Tsugaru Warm Current. The WNP is known to be a productive fishing ground for several pelagic species. In this work, I used geo-referenced skipjack tuna fishery data and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) images as presence only proxy data for pacific saury and squid.

For environment, I used satellite remotely sensed sea surface temperatures (SST) (MODIS & Optimally interpolated AVHRR-AMSR); chlorophyll-a (SSC) (MODIS & SeaWiFS); sea surface height anomaly (SSHA), sea surface height (SSH) and eddy kinetic energy (EKE) (AVISO); diffuse attenuation coefficient (K490) (MODIS), and wind speed (WS) (SSM/I). In addition, SSTs generated from Miroc 3.2 model as well as mixed layer depths (MLD) and sub-surface temperatures generated from a 4-dimensional variational (4D-VAR) model data were used.

2.1 Habitat characteristics of skipjack tuna using GAMs

Habitat characteristics of skipjack tuna were determined using fishery data and four remotely sensed oceanographic parameters using GAMs. Fifteen GAMs were constructed using skipjack tuna catch per unit effort (CPUE) as the response variable and SST, SSC, SSHA and EKE as environmental predictors. A four parameter GAM was selected from the set of 15 based on the highest deviance explained and the lowest akaike information criterion (AIC) value. This model was used to make habitat predictions for skipjack tuna in the WNP.

2.2 Potential impact of global warming on skipjack tuna habitat using ENFA

To study the potential impact of global warming on skipjack tuna habitat in the WNP, I used satellite remotely sensed data and ENFA models. Fishery presence-only monthly resolved data (2004-2005) for skipjack tuna were used, together with SST, SSC, K490, SSH and WS as skipjack tuna habitat descriptors. Based on IPCC projections, I used predicted SSTs from the Hires Miroc 3.2 model data for 2025, 2050 and 2100. The 2004-2005 skipjack tuna and environment data layers were used to construct ENFA models and generate HSI from February to November. Using the constructed ENFA models, I predicted HSIs from 2006-2008 and also based on predicted SSTs for 2025, 2050 and 2100. Comparisons between HSIs generated by base models and by models generated by predicted SSTs were made using the Kolmogorov-Smirnov test. Distributions of MLDs and temperature-depth profiles derived from a 4D-VAR data assimilation system, at fishing locations were also examined.

2.3 Assessing ecological interactions between skipjack tuna, pacific saury and squids using MaxEnt models

To assess possible ecological interactions between skipjack tuna, pacific saury and/or squids in the WNP, skipjack tuna fishery presence-only data, proxy presence-only data derived from DMSP/OLS nightlight images and satellite remotely sensed environmental parameters were used. Using skipjack tuna presence-only distributions derived from fishery data and satellite remotely sensed SST, SSC and SSHA images, monthly (August-November) HSIs were calculated using models constructed in MaxEnt software for the area defined by 33-42° N and 141-160° E. A second set of HSIs for the same area was calculated using presence-only data derived from DMSP/OLS nightlight images and the same set of environmental parameters. Model performance was evaluated using the area under the curve (AUC) statistic and Jackknife tests. Maps of both sets of HSIs were compared monthly and areas of overlap identified using longitudinal transects and joint probabilities.

3.0 Results and discussion

3.1 Habitat characteristics of skipjack tuna using GAMs

Based on the 4-parameter GAM, SSTs ranging from 20.5-26 °C, relatively oligotrophic waters (SSC, 0.08 to 0.18 mgm^{-3}, 0.22-0.27, and 0.3-0.37 mgm^{-3}) zero to positive anomalies (SSHA, values 0-50 cm), and low to moderate EKEs (0 to 200 cm^2s^{-2} and 700 to 2500 cm^2s^{-2}) significantly ($p<0.01$) influenced skipjack tuna habitat. Predicted CPUEs showed a trend consistent with the north-south migration of skipjack tuna. Validation of predicted CPUEs with observed CPUEs, pooled monthly was significant ($p<0.01$, $r^2=0.64$). SST explained the highest deviance in GAMs hence was considered the best habitat predictor. Temperature limits horizontal and vertical distribution of skipjack tuna, and this varies by region and size. Preference for relatively low chlorophyll waters, especially on the frontal edges of warm oligotrophic waters has both physiological and trophic implications. This enables skipjack tuna to not only locate and forage on the periphery of highly productive frontal or upwelling zones, but also stay within tolerable temperatures. SSHA and EKE showed relatively lower effect as predictors of skipjack tuna habitat compared to SST and SSC.

3.2 Potential impact of global warming on skipjack tuna habitat using ENFA

ENFA models predicted skipjack tuna habitats on both short-term and long-term scales. Long-term habitat predictions based on predicted SSTs indicate global warming is likely to cause expansion of suitable habitats of skipjack tuna northwards, from February to June. I found significant changes in habitat suitability, associated with rise in SST in this period. After July, SST rise had a negative or marginal impact on HSI. Skipjack tuna habitat suitability was consistent with declining MLDs from February to November. Model predictions indicate that MLDs are likely to be shallower in the 21st century, as the WNP Ocean changes due to global warming. It has been shown that as a result of surface warming, the WNP would stratify further (with the MLD becoming shallower) in January and February which would cause the spring bloom to occur 1.5 months earlier. I suggest that warming induced shoaling of MLDs could create more favorable conditions for skipjack to migrate north earlier, or delay the onset of their southward migration.

3.3 Assessing ecological interactions between skipjack tuna, pacific saury and squids using

MaxEnt models

From skipjack tuna fishery data and DMSP/OLS images for 2004 in the WNP, it was apparent that the period August to November is the most likely period when the fisheries of the three species are in close proximity. Kernel density estimations of DMSP/OLS locations showed two sets of light distributions separable by latitude and SST. High AUC values (>0.9) indicated excellent ability of MaxEnt models to discriminate from occurrence by chance. Results of Jackknife tests showed that SST had the highest contribution to skipjack tuna models while for the OLS models, SST shows high contribution only in September and October. Maps of monthly HSIs indicated a pattern where high suitability areas for skipjack tuna were predominantly in the south while those derived from OLS images were north of the skipjack tuna HSIs. The proximity between high suitability areas from the two models in each month increased from August to November when a clear spatial overlap was evident. This pattern was confirmed by two dimensional transects of HSIs plotted for selected longitudes where highly suitable areas for both models showed overlaps in October and November.

4.0 Key issues, future perspectives and conclusions

In this thesis work, I highlighted four key issues that are the concern of researchers and also areas that could shape future research directions in this field. These are (but not limited to), (i) continuity in global coverage of satellite remotely sensed data streams, especially ocean color; (ii) integration of satellite remotely sensed datasets with in-situ measurements and products from oceanographic models at spatial and temporal time-scales that can accurately resolve local to meso-scale processes in three-dimensions; (iii) refinement of prediction models to accommodate both fishery predictions and fishery management strategies based on scientifically underpinned findings and (iv) uncertainties associated with species' genotypic or phenotypic adaptations to changing temperatures are difficult to quantify in habitat suitability models.

I concluded that:

i. Skipjack tuna distribution and catch rates in the WNP are profoundly influenced by SST, SSC concentrations, as well as meso-scale features such as eddies and strong currents. SST was found to be the main variable affecting occurrence and catch rates.
ii. Global warming will initiate early migrations of skipjack tuna to higher latitudes, 1-2 months earlier by 2050 and beyond. Warming could also delay the southward migration of skipjack tuna and consequently increase their residence times at higher latitudes. These conclusions were arrived at by varying only SST in habitat suitability models. It is expected that the results could improve significantly if more parameters are varied simultaneously, e.g. using predicted SSTs and SSC concentration data for 2050 or 2100.
iii. Habitat overlaps between skipjack tuna and pacific saury and/or squids existed between August and November in the WNP, when skipjack tuna has reached the northern most extreme during the northern migration. It will be interesting to see how such interactions will be affected by global warming of world oceans.

学位論文審査の要旨

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近年、国連海洋法により、排他的経済水域（EEZ）内での充分な資源の開発利用と、自国にとって必要以上の資源を他国に利用させせることを義務付けられている。このような状況から、わが国周辺水域の環境収容力を明らかにすることを目的に、従来の資源量推定法に加え、広い海域の資源量や生産環境を、短時間かつ高精度に探査できる新しい資源量推定法やリアルタイム海洋生物資源環境モニタリングシステムを開発することが急務とされている。そして、持続的に海洋生物資源を利用する視点や資源回復計画案の策定上からも、いつ、どこに、どのくらいの資源が利用可能かリアルタイムで知る必要がある。

本研究で対象としたカツオ(*Katsuwonus pelamis*)は、北太平洋において日本の竿釣り漁業とまき網漁業の対象魚であり、中西部太平洋では、カツオの総漁獲量は年平均 160 万トン以上もあり、商業的にも生態学的にも重要な漁業資源である。経済的な観点からは、この種は高経済価値があり、広い市場性もある。本種は、太平洋の熱帯域から亜寒帯域に出現し、その分布域は、適水温帯の分布に合わせて西側で南北に広く、東側では狭くなる。日本近海（北緯 20 度以北）では、2008 年まで 11.2 万トンから 18.3 万トンの間で推移していたが、2009 年には 8.1 万トンと大きく減少した。このように 2009 年以降、西部北太平洋の日本近海での不漁が続き、熱帯水域における高水準の漁獲が、我が国近海を含む高緯度域への回遊減少を引き起こしている可能性も議論されている。このことは、本種の潜在的な漁場がいまだ完全に理解されておらず、本資源は開発途上であることを示している。特に北西北太平洋において、カツオの高生産漁場（生息域ホットスポット）を制御している海洋環境条件について不明な点は多く、それを明らかにすることは非常に重要である。

これまでのカツオ資源と生態に関する調査研究では、調査船による漁獲・観測データ

や標識放流・再捕などにより、その分布・豊度や回遊経路が調べられている。しかし、年間を通した生息海域全体での分布・移動、あるいは海洋環境と統合した漁場形成に関する知見は断片的である。

そこで本研究は、主に人工衛星により観測された海面水温、クロロフィル *a* 濃度、海面高度データおよび竿釣り漁獲データを用いて、カツオ生息可能海域の時空間変動を明らかにし、カツオ漁場形成に関わる海洋環境との関係を明らかにすることを目指したものである。さらに空間情報学的な手法を用いて、温暖化に対してカツオ生息可能海域が将来どのように変化するかを推定したものである。

特に審査員一同が評価した点は以下の通りである。

1. 一般化加法モデル（GAM: Generalized Additive model）を用いて、カツオの好適海洋環境は、海表面温度が 20.5～26°C、クロロフィル濃度が 0.08～0.37 mg m^{-3} の貧栄養海域、海面高度偏差が 0～50 cm の範囲であることが明らかにした。さらに 15 の GAM モデルを構築して、その中から統計的に最適なモデルを選択して漁獲データのない期間のカツオ生息域を推定することを試みた。
2. 生態的ニッチ要因解析法（ENFA: Ecological Niche Factor Analysis）を用いて、IPCC の将来予測モデルに適用して、カツオ生息域の変化について 2025 年、2050 年、2100 年の 3 ケースをシミュレーションした。その結果、このまま温暖化が進むと 2050 年には、現在より 1-2 ヶ月早く北に漁場が形成されることを示唆した。
3. 4 次元同化モデルの計算結果を用いて、カツオの生息水深の季節変動を明らかにした。温暖化による混合層厚さの変化に対して生息水深が影響を受けることを示唆した。
4. カツオとカツオの餌生物のイカ類との生息域の重複が秋季に大きくなることを明らかにし、さらに温暖化によりその度合いが大きくなることを示唆した。

本研究は、衛星リモートセンシングと GIS（地理情報システム）技術を応用して、どのようにカツオが海洋環境に応答しているか理解し、そのカツオ生息域空間モデルの開発に挑戦したものである。本研究を発展させることにより、“オペレーショナル”水産海洋学をさらに一歩進めて、この空間モデルを実際の漁業へ応用して、効率的で持続可能な漁業の推進に貢献できることを期待している。

審査員一同は、本研究が、カツオの生息域空間モデリングに関する統合的な知見を得たものと高く評価し、申請者が博士（水産科学）の学位を授与される資格のあるものと判定した。