学位論文内容の要旨

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学 位 論 文 題 目

An integrated approach of habitat suitability model for management of Japanese scallop (*Mizuhopecten yessoensis*) aquaculture: a comparative study in Funka Bay and Mutsu Bay, Japan

(ホタテガイ養殖管理のための好適生息域モデルの統合的アプローチ：噴火湾と陸奥湾との比較研究)

1.0 Introduction

Japanese scallop (*Mizuhopecten yessoensis*-"Hotate-gai") culture has grown to be the most successful marine shellfish farming venture in Japan. Production is about 500 thousand tons per year with the value reaching about 840 million USD. The main operational areas of scallop culture are Saroma Lake, Sea of Okhotsk and Funka Bay, Hokkaido and Mutsu Bay, Honshu. The success of scallop farming can be partly attributed to the ideal habitat and environment provided by these waters for the growth and survival of scallops. With the development of Geographical Information System (GIS) Multi-criteria Evaluation (MCE) for scallop suitability sites in Funka Bay and the preliminary Mutsu Bay (studied herein) spatial-temporal scallop aquaculture models, any differences in aquaculture sites and performance are likely to be related to changes in the marine environment. Since both bays have similar climate forcing and hanging scallop culture. Such feedback would be useful in determining a scientific proof of concept of a framework of argument on the changes in scallop aquaculture stocks due to mortality as it was reported in Mutsu Bay but not in Funka Bay. Meanwhile, on a global scale, comparative studies on the changes in marine environment in areas with similar climate forcing are lacking. This paper assesses the Japanese scallop habitat suitability using comparative modelling and dominant marine environment indicators in Funka Bay and Mutsu Bay, Japan. Thus aquaculture managers can mitigate extreme environmental impacts of for example, extreme sea temperature, water volume and heat fluxes by ascertaining the stock level of scallop larvae as well as the stock to be caught.

2.0 Data and methods

2.1 Study area

The study area included Funka Bay and Mutsu Bay in Japan between 40.60°N – 42.75°N and 140.18°E – 141.40°E. In both bays, scallop hanging culture method is used. Funka Bay is a semi-enclosed bay in southwest Hokkaido. The bay is affected by the inflow of two water masses: Tsugaru warm water from autumn to winter and Oyashio water (a subarctic oceanic water mass) from spring to summer. Comparatively, Mutsu Bay is a large semi-enclosed bay located at the north end of Honshu Island. It is mostly shallow except for regions around the tip of the Natsudomari Peninsula and at the bay entrance (near Sotogahama) with about 80 m water depth. It is affected by the inflow of Tsugaru warm water from autumn to winter.

2.2 Data sources and processing

The satellite data used included 1 km resolution of Sea surface temperature (SST), Chlorophyll-*a* (Chl-*a*) and Secchi Disk Depth (SDD), which were derived from the

Moderate Resolution Imaging Spectroradiometer (MODIS). Advanced Visible and Near Infrared Radiometer (ALOS-AVNIR-2) images were downloaded from the AUIG website for extracting socio-infrastructure and constraint data, and were processed based on existing methods in the region. SDD or transparency (Kd490) composite images were produced based upon existing literature. Bathymetric data were obtained from the Japan Oceanographic Data Centre (JODC).

Scallop production data (2008-2011) for both bays were also employed. The data from *in situ* measurements included buoy SST from marine buoys deployed in Mutsu Bay and *in situ* Chl-*a* for Funka Bay. Daily Oceanographic data of sea temperature, depths and velocity were derived from model-derived four dimensional-variational (4D-VAR) data assimilation system developed from Kyoto University, Japan. Water volume and heat fluxes were estimated using standard existing formula.

Towards integrated assessment of scallop environment, a comparative spatio-temporal suitability model for Funka Bay and Mutsu Bay, Japan was developed in the initial stages. The main purpose of model comparison of the two bays was to establish the aquaculture risks that existed in Mutsu Bay that caused mortality of scallops, but not in Funka Bay. The output of the suitability scores during the threshold of the Coastal Oyashio (CO) current and Tsugaru warm current (TWC) were associated with the potential effects of such currents on aquaculture. The final stage involved the use of ecological indicators such as sea warming to assess their relation with aquaculture suitability.

3.0 Results and discussion

3.1 Spatio-temporal modeling and indicator performance

Though both bays have similar climate forcing, differences in indicator performance in the scallop culture models signaled differences in the magnitude of the causes of marine environment change between the bays. Thus Funka Bay had a large proportion (51.1%) than Mutsu Bay (13.7%) of the aquaculture operational area with a score of 8 in the best performed model of 2009. The 2010 model had the least performance with a score of 8 recording lower proportions of 7.4% and 4.8% for Funka Bay and Mutsu Bay, respectively. Additionally, the study revealed elevated levels of Chl-*a* in Funka Bay in 2010, and SST in Mutsu Bay in August-September, both associated with low performance of the 2010 model.

Both bays recorded the highest scores in both May and November suitability models that were evenly distributed in the scallop culture areas, attributed to potential effect of CO (for Funka Bay only) and TWC (in both bays). The CO (in Funka Bay) and TWC (in Funka Bay and Mutsu Bay) have been regarded as the main causes of the changes in marine environment in both bays. The models developed displayed a high degree of reliability since the suitability scores were highly consistent with the actual *M. yessoensis* aquaculture operations.

3.2 Sea temperature distributions, water volume and heat flux

The summer 2010 extensive and broader depth (≈ 0-18 m) exposure to warmer sea temperatures (>24^{0}C) was linked to scallop mortality in Mutsu Bay. Additionally, Mutsu Bay had high total volume fluxes than Funka Bay, related to high velocity of water and heterogeneous topography of the former. The lower total volume and varying total heat flux in summer 2010 in Mutsu Bay was linked to unstable scallop habitat. The less saline CO advection in March-May was linked to minimal effect in volume and heat loss in Funka Bay. The more saline TWC in autumn-spring was associated with increased heat gain and

water volume in both bays. Other than Chl-*a* and SDD that affects scallop growth and survival, only the seawater temperature emerged as the main factor that is susceptible to oceanic water volume and heat flux fluctuations in Mutsu Bay only.

3.3 Climate change effect on scallop aquaculture

Further increase in sea temperature in the future due to global warming is likely to decrease the most suitable sites in Funka Bay and loss of such sites in Mutsu Bay for scallop farming. Meanwhile, least scallop production areas may show minimal change or no vulnerability to climate change as opposed to high scallop production areas. Thus differences in marine environment could influence coastal (scallop) aquaculture development in the future. This would imply that high production areas will continue to practice scallop farming but with moderate scallop production estimates. Such concepts should be considered by scallop farmers in such areas in planning, for example, for scallop breeding programs designed to increase the temperature tolerance of cultured species.

4.0 Conclusions and further considerations

Due to scallop marine environment change, differences in aquaculture and model performance were noted. For example, elevated sea temperature in Mutsu Bay in August-September 2010 which was associated with low performance of the 2010 model was linked to mortality of scallops based on daily sea temperature-depth visualizations; further increase in sea temperature in the future due to global warming is likely to shrink or minimize the most suitable sites for scallop farming in Funka Bay and perhaps render the most suitable sites in Mutsu Bay ecologically unreliable. The potential effects of CO (in Funka Bay) and TWC (in both bays), as well as indicator concentrations were noted as one of the main causes of the changes in marine environment, which are likely to cause the differences in scallop culture suitability in both bays.

The present study recommends: (i) mitigation of temperature tolerance of cultured species that is needed in order to minimize mortality and increase production e.g. through late deployment of hanging culture in highly vulnerable areas to climate change, (ii) comprehensive data on scallop abundance, mortality, and growth are needed to plan on management system that is based on release of cultured juveniles, removal of predators and rotational harvesting to monitor changes in marine environment in less vulnerable areas to climate change, (iii) adaptive harvesting, proposed as an effective way to avoid impacts of toxic blooms to the bivalve aquaculture industry in coastal areas with frequent occurrences of toxic dinoflagellate blooms. Thus, with toxic algal bloom occurrences having the potential to affect both biophysical and socio-economic aspects of aquaculture site selection, there is need to consider such scenarios as a future problem in integrated scallop aquaculture management, (iv) additional inclusion of Sea Surface Salinity (SSS) into the model in the future could show model performance in different thresholds of salinity. This is because, for example, low-salinity water has been found to be distributed along the coast of Funka Bay, formed by snowmelt runoff in March for both years and was most dominant in July. Such concepts could be a scientific basis for aquaculture planning on proper designated system of larval distribution and stock management of cultured species to minimize mortality and economic losses.