論 文 の 内 容 の 要 旨

論文題目　Numerical Analysis of Integrated Multi-Trophic Aquaculture for Biomitigation of Marine Ecosystem
（生物を用いた海洋生態系保全のための複合養殖の数値解析）

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Since overfishing leads to a consistent decline in global fisheries landings, marine aquaculture exhibits its potential to play a major role in satisfying world seafood demand in the future. However, intensive aquaculture is facing the self-pollution problem due to fish farming operations. Water environment has been deteriorated rapidly due to inorganic wastes such as nitrogen and phosphorus dissolved into water, as well as organic wastes from unconsumed feed and fish feces loading on the sea floor. They have caused harmful algal blooms and hypoxic or anoxic water, respectively. Such environment deterioration often produces negative consequences for fish farmers such as death and disease of cultured fish. Fish farmers have tried to reduce the negative effect on the environment of the aquaculture site by controlling the density of cultured fish. They have also moved their fish cages, so that fish in the cages can escape from harmful algal blooms or hypoxic water. However, an effective solution to self-pollution problem could not be found.

As an alternative approach to avoid or mitigate the negative effects by and on intensive aquaculture, co-culture technique has received full attention in recent years, named Integrated Multi-Trophic Aquaculture (IMTA). The aim of IMTA is to achieve sustainable development of aquaculture by means of recycling wastes as food resources through co-cultivating the targeted species with others which have different feeding habits in different trophic levels, in order to improve the efficiency and productivity of intensive mono-culture systems consequently. Wastes released from the targeted species could become food sources for others; for example, particulate organic wastes can be utilized by suspension feeders as well as deposit feeders. Dissolved nutrients can be absorbed by seaweeds. IMTA will minimize wastes and alleviate the adverse impacts on the environment.

Material and energy flows need to be studied quantitatively in order to assess the optimal design of IMTA and the biomitigation efficiency. However, complex interactions between co-cultured species and natural physical and ecological environment are difficult to be fully examined under partially balanced experimental setups. Therefore, a mathematical model will be one of the useful tools to estimate the biomitigation efficiency of IMTA, and to facilitate the understanding of local physical, chemical, and biological characteristics, as well as the physiological and metabolic characteristics of the co-cultured organisms, for optimizing the design of IMTA.

Since an identical mathematical model has not been developed for IMTA system yet, this doctoral thesis attempts to establish a model framework that considers natural biogeochemical fluxes in the surrounding environment of IMTA site. The main objectives of the present study are: (1) to understand the material cycle in IMTA site; (2) to assess the role that an IMTA system plays in the biomitigation of marine ecosystem; and (3) to offer useful suggestions for the design of IMTA system.

In the present thesis, the numerical model for IMTA is developed based on a three-dimension hydrodynamic and ecosystem coupled model, named Marine Environmental Committee (MEC) ocean model. In order to assess the biomitigation efficiency of IMTA system on marine ecosystem, four submodels are originally developed and integrated into the MEC ocean model in aspects of hydrodynamic, ecosystem, and individual-based components. The drag of fish cage submodel describes details of the drag force produced by fish cages and explores the impact of fish cages on water current. This submodel is integrated in the hydrodynamic submodel for the first time. The diffusion of wastes submodel is also developed and considered in the pelagic ecosystem submodel for understanding the dynamic advection and diffusion of wastes around aquaculture area. The newly developed individual-based component consists of Japanese sea cucumber and seaweed submodels. The Japanese sea cucumber digests the particulate organic wastes. Its submodel is originally developed to describe the dynamic biological processes for assessing the elimination efficiency of organic wastes. A series of model parameters are calibrated based on the experimental data in literature, and then the submodel of Japanese sea cucumber is validated by the experimental results in laboratories. The existing seaweed submodel is coupled with MEC ocean model as well as Japanese sea cucumber submodel. The integrated model is applied to evaluate the removal capacity of wastes by sea cucumbers and seaweeds in IMTA system in Gokasho Bay of Mie Prefecture, which is the target area for the aquaculture of red sea bream. The integrated model was validated by several observations and the results of several numerical simulations could achieve the following results.

First, fish cages exert an influence on water current both in velocity and direction aspects, and the reduction in water current velocity is about 38% at the maximum where fish cages are arranged at upper layers. The maximum flux of particulate organic wastes (POW) occurs in summer with approximately 3 gC m^{-2} d^{-1}. The contribution of fish fecal matter is dominant during winter (ca. 80%), while in other seasons waste fish feed is the main source of POW. The distribution of POW near sea bottom shows that the organic wastes not only mainly load on the sea floor of the areas just beneath fish cages, but also in the western area from aquaculture site. Aquaculture wastes may be trapped due to reduction in water current in the upper layer, and are settled on sea bottom in the western area from aquaculture site due to westward current in the lower layer from August to November. On the contrary, wastes settle directly on sea bottom due to relatively strong downward water current from January to April. Such information will provide useful reference for selecting the time and location of ranching sea cucumbers and planting seaweeds in IMTA system. However, as a large amount of aquaculture wastes are released from fish farm, water environment deteriorates sharply. The hypoxic waters appear in the lower layer in summer, while they do not upwell to sea surface due to the narrow channel. The concentration of dissolved inorganic nutrients increases in the upper layer due to intensive aquaculture, while the concentration of phytoplankton is higher in the head of Hazama-ura in Gokasho Bay due to a lower rate of water exchange. As a result, the negative influence of intensive aquaculture on the cultured fish can be currently reduced by the characteristics of the site topography; however, the aquaculture is still facing a high risk of death or diseases of the cultured fish.

Then, it was found from the numerical simulation using individual submodel of Japanese sea cucumber that the food conversion ability of sea cucumbers varies with body size, especially between small size (less than 10 g) and large size (more than 10 g). If a constant value for food conversion ratio is used for all size categories, the Japanese sea cucumber submodel will overestimate their growths when it is applied to small size sea cucumbers since the submodel was developed based on the laboratory experiments of larger sea cucumbers. The digestive organs of smaller sea cucumbers may not be fully developed. The overestimation can be overcome by using a body mass function for the food conversion ratio which reflects various food conversion abilities of sea cucumbers in different body sizes.

Finally, it was estimated from the numerical simulation using the integrated model for IMTA that water environment can be improved by planting seaweed in the upper layer of aquaculture site in Gokasho Bay. The concentration of phytoplankton can be controlled by the seaweed; therefore, the risk of harmful phytoplankton blooms will be reduced. On the other hand, the concentration of bottom DO is slightly increased by ca. 15% at the maximum due to the reduction of organic wastes through the ingestion of sea cucumbers, when the density of sea cucumber is 1.2 ind. m^{-2}. The increased initial density of sea cucumber (3.9 ind. m^{-2}) could further improve the concentration of dissolved oxygen. However, the biomitigation efficiency of sea cucumber is not significant since the concentration of dissolved oxygen increases by only around 1 mg L^{-1} during summer. Therefore, the other species of deposit feeders, such as shrimp, may be further considered for effective biomitigation.

The present doctoral study may supply a useful mathematical tool not only to evaluate the biomitigation of IMTA system but also to offer suggestions on the optimal design of IMTA. In future studies, the present model should be further applied to more IMTA systems to practice the universality of the integrated model.