論文の内容の要旨

Thesis Summary

論文題目　Numerical analysis of the variation in ecosystem with the recovery of aquaculture after great earthquake disaster in coastal seas

（沿岸海域における大震災後の養殖の復旧に伴う生態系の変動の数値解析）

氏　　名 周　金鑫

Sanriku Area in the northeastern side of the island of Honshu, Japan, owns a typical ria coast, and by taking full advantage of this particularly favorable topography, the wisdom of the industrious people living there has ushered in a prosperity of aquaculture industry, through the constant efforts of generations after generations. For example, in the Onagawa Bay, the southern part of Sanriku Coast, the activities toward exploitation of living marine resource commenced since Heian Period and yet this place has developed from an unrecognized fishing village into a thriving fishery production base of Japan — the largest aquaculture salmonid food supply across the country together with a well-known shellfish aquaculture. However, a rapid expansion in intensive salmonid aquaculture, which is based on cage culture in the nature of fed aquaculture, has led to a severe environmental concern due to the waste byproducts from these cultivation cages. For example, Shizugawa Bay, accompanied by a boom in salmonid aquaculture in the 1970s, has been reported an environmental deterioration problem, in which the Chemical Oxygen Demand (COD)

of bottom sediment exceeded 100 mg g^{-1} dry below the fish cage. Therefore, the concept of sustainable aquaculture has been proposed and endeavors to date are still underway through trial and error from the scientific perspective, such as ecosystem-based aquaculture operations, aquaculture nutrient credits and the assessment of aquaculture energy efficiency. Consequently, the circulation of matter (energy) in aquaculture ecosystem, together with a holistic view of ecosystem, merits an increasing attention to serve a sustainable aquaculture development.

On another hand, Sanriku Area was, unfortunately, violently shaken by a mega-quake in 2011 with an apparent topographical deformation, not to mention artificial facilities on land and aquaculture installations floating at the sea surface. Corresponding to the importance of aquaculture industry, the recovery of aquaculture along the Sanriku Coast has become the focus of both policymakers and scientific researchers, especially in the Onagawa Area where aquaculture is a very symbolic industry and its related industries are the main source of commerce. However, the uncertainty due to the altered environment inhibits the full understanding toward circulation of matter (energy) and deprives the accumulated previous research results of objective credits. To fulfill these gaps, an ad hoc national project call "Tohoku Ecosystem-Associated Marine Sciences" (TEAMS) was launched since March 2012, in which a field center was built in Onagawa Area to support its fishery reconstruction. Until now, a volume of observational data have been collected for the ecosystem variation; however, the task to investigate matter (energy) flow within such a complex system is beyond the capability of the present monitoring technology, and therefore results in an improved awareness and practice of numerical simulation to integrate these interactions. In terms of mathematical modeling, it is not rare to numerically resolve the ocean circulations, e.g. Princeton Ocean Model, the pelagic ecosystem, e.g. PlankTOM5 model, or the benthic-pelagic coupled ecosystem such as the Ecological Connectivity Hypoxia Model; likewise, the immense manpower has been invested to develop the individual biological models, e.g. the von Bertalanffy growth model, the interfaces within the food web, such as Ecopath with Ecosim software, and even the interactions between the low- and high-trophic environment such as DEPOMOD software. Woefully, relatively little modeling research has attempted to integrate all above components and serves as a productive tool for ecosystem services in aquaculture industry.

In this study, Marine Environmental Committee (MEC) ocean model, a hydrodynamic pelagic-benthic coupled low trophic numerical model, was expanded by 1) introducing individual aquaculture species, 2) coupling food web as in Ecopath and primarily applying it to high trophic macrobenthos, and 3) integrating corresponding physical alterations due to the former modifications. Further, it was tailored for the situation in Onagawa Bay by taking full consideration of its boundary conditions, the model parameterization as well as validation, on the basis of previous experimental results and long-term observation data, and then it examined the ecosystem variation with the recovery of aquaculture. This study originally analyzed the ecosystem variation in a systematic approach, with an application to an aquaculture innovation, and moreover, this model laid the foundation for the possible numerical approach toward synthetic food web between low- and high-trophic species, to the best of knowledge, which was the pioneer trial among 3-D ocean models.

As a result, the new model was successfully run, with an evaluation coefficient of 0.98 at tidal elevation and that of 0.99 at dissolved oxygen. For the characteristics of Onagawa Bay, it was found from the variation of water salinity that Onagawa Bay was affected by the nearby large river, Kitakami River. During the rainy season, the discharge from Kitakami River was carried by the ocean current and moved southward, which eventually affected the Onagawa Bay. Meanwhile, it brought the nutrient, like silicate-silicon, into the Onagawa Bay as well. Generally, the current flows were fast around the bay mouth. However, only a branch of water with small velocity rushed into the inner bay, resulting in a rather slow current flow in the inlet and low frequency of water exchange. Therefore, introducing the aquaculture facilities caused slight effects on water flows, with the maximum resistance on current flows of 1 mm s^{-1}. Contrary to the direct effects on drag force, aquaculture may cause the environment degradation by the waste accumulation. From the point of water exchange, the time taken to exchange water body in Onagawa Bay increased from 5–10 days in 2011 to 30–35 days in 2015. Moreover, from the tracer simulation, it was found that aquaculture only around bay mouth, due to the high current flows and water exchange rates, escaped waste accumulation, and especially in the southern bay, it was simulated to possibly have a severe environmental deterioration due to the high concentration of aquaculture waste.

For pelagic environment, first of all, the concentration of chlorophyll-*a* was well simulated, and a significant decline of phytoplankton was found from both observation data and simulation results with aquaculture. The concentration of nutrient, typically nitrogen, was underestimated compared to the observed level; however, the order of total inorganic nitrogen, when taking the cellular nitrogen in simulation, matched well with that of observed concentration in seawater. It indicates that nutrient was excessively exploited by phytoplankton in simulation and a furtherance parameter tuning may be of great importance. The two kinds of aquaculture operation in Onagawa Bay put different effects on environment. The fish cage aquaculture was simulated by a predefined weight increase and accordingly released nutrients as well as faeces into surrounding area. However, the long-line aquaculture and the growth of shellfish were depended on the pelagic environment. Even though, at present, only the order of shellfish production has been reached, the simulation results unveiled the possible relation between the increased production and the attenuated primary production in Onagawa Bay. Then, the benthic environment closely interacted with variation in the pelagic environment. With the shrunk-down of phytoplankton assemblage, the carbon burden into the benthic environment eliminated and it directly affected the growth of those species that feed on suspension organisms, e.g. the species in the Class Bivalvia. On another hand, the excessive faeces and uneaten feed around the aquaculture farms, instead, promoted the biomass accumulation for the macrobenthos that feed on deposit, e.g. the species in the Phylum Echinodermata. Finally, the concentration of sulfide in sediment was the most complicated, and only the fluctuation tendency was simulated in this work. Generally, the concentration of sulfide in Onagawa Bay was low and far below the pollution threshold; however, the reason was thought to be different from area to area. Below the fish cage, although additional carbon sedimentation resulted in the pressure on benthic environment, the following bloom of deposit-feed macrobenthos, to some extent, mitigated this aquaculture effects and protected the benthic environment. Conversely, around the long-line aquaculture, the high dense aquaculture species over-used the phytoplankton instead reduced the burden of benthic environment, and their metabolic waste was also fully utilized by pelagic organisms, due to slow water exchange.