学　位　論　文　の　要　旨

論文題目

Environmental and seasonal dynamics altering the primary productivity in Bingo-Nada of the Seto Inland Sea, Japan
（瀬戸内海備後灘の基礎生産性を左右する環境的・季節的動態に関する研究）

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Chapter 1. General introduction

The Seto Inland Sea is the largest semi-enclosed sea in Japan. From the 1960s, due to the heavy industrialization and sewage dumping, the sea experienced heavy eutrophication as well as severe red tides. In 1978, Act on Special Measures concerning Conservation of the Environment of the Seto Inland Sea was enforced. Under this law, decreases of chemical oxygen demand, total nitrogen and total phosphorus have been called, and the levels of these elements have decreased since 1980s until recently. In response to these favorable effects of the law, ironically, “oligotrophication” of the sea has been a concern since the 2000s. With oligotrophication, fish catches of the sea dropped from 485,000-ton year^{-1} in 1985 to 157,000-ton year^{-1} in 2016. Such decrease in catches likely involves diverse factors inhibiting fisheries; in addition, oligotrophication may hinder the biological production that used to prosper in the sea.

Bingo-Nada is located at the center of the Seto Inland Sea and is characterized by a low exchange rate with seawater from the outer oceans and a relatively low supply of riverine waters from the land. The study area, off Fukuyama City of Bingo-Nada, was once an active fishing area, characterized by Nori (*Pyropia* seaweed) culture and wild fish catches (e.g., Japanese anchovy), however; the Nori production has been constantly decreasing since 1988, dropping from approximately 1.6 hundred million sheets year^{-1} to an almost half of that level in recent years, similarly, and the fish catch decreased from over 12,000-ton year^{-1} in 1982 to under 4,000-ton year^{-1} in recent years. Based on the facts that the entire Seto Inland Sea has undergone oligotrophication and that Bingo-Nada is one of the most sensitive areas in the sea receiving significant feedbacks from the land, it is plausible that the current oligotrophication and consequential environmental changes reduce the productivity of the area. In addition, some observations have reported that the recent trends of notable diatoms’ bloom in winter season which could cause decrease of Nori production and lack of so-called “spring bloom” of phytoplankton population. Regardless to the oligotrophication, incidences of red tide have been constantly reported in summer. Thus, it is plausible to think that, in addition to the oligotrophication, there might be recent changes in seasonality of phytoplankton occurrences as well as their group shift, those could be derived from recent environmental and/or climate changes. However, almost for 20 years, survey has not been conducted in this area, and thus the fact remains unknown. Therefore, to determine the most recent trends in the primary productivity of Bingo-Nada and to find possible causes deterring local fishery catches, monthly surveys for four years were conducted (Chapter 2).

In an aim to increase primary productivity at Bingo-Nada, a simple and low-cost method, which improves fishery area, was also proposed. Sea-bottom plowings were conducted under cooperation with the fishermen at Bingo-Nada to improve bottom environment of their fishery area and to increase phytoplankton population by seeding resting cells of diatoms those accumulated at the bottom to water column (Chapter 3).

Based on the results and discussions of Chapters 2 and 3, overall problems that may hinder biological productivity of Bingo-Nada, and possible countermeasure to relief the situation and future perspectives were proposed as a general discussion (Chapter 4).

Chapter 2. Seasonal dynamic of the primary productivity in Bingo-Nada

Primary productivity was estimated by pulse amplitude modulation (PAM) fluorometry. This methodology enabled to estimate not only primary productivity but also contributions of environmental components (i.e., light, turbidity, nutrient levels, etc.) those could alter the productivity. By employing this, environmental and seasonal dynamics altering recent primary productivity were investigated by the monthly on-site samplings at Bingo-Nada from May 2014 to March 2018. Also, occurrences and composition of phytoplankton were monitored, and those dynamics were interlinked with various physicochemical and climatic factors.

The most notable phenomena were diatom blooms in every January, which had not been observed in the past studies. In the PAM measurement, the initial slope of electron transport rate (rETR) versus light (α parameter) increased in the population, indicating low-light adaptations of the diatoms enabled high photosynthetic activity in this low-light season. These winter blooms caused drastic consumption of inorganic nutrients, that further led insufficient nutrient levels those continued until April. Consequently, the nutrient depletions resulted in lowering photosynthetic parameters ($rETR_{max}$ and α) in April, caused the lowest chlorophyll *a* and drops of the primary production rate (PPR_{ETR}) in this spring season, regardless to the consensus that spring is productive season in temperate areas. A principal component analysis (PCA) reveled the inability of photosynthesis was attributed to the depletion of inorganic nitrogen (DIN) in April. Similarly, as the case in April, the photosynthetic parameters (Fv/Fm, $rETR_{max.}$and α) dropped in September; however, being different from the spring, the PCA indicated these drops were not due to the nutrient depletions but reduction in light to a level inhibiting photosynthesis. September and October were recognized as the transient period from the high-light season to the low-light season. In addition, elevations in the diffuse attenuation coefficient (turbidity) from August to October, mostly caused by high precipitation due to the autumn rain front, and by activation of vertical mixing of the water column, were assumed to affect the photosynthesis reduction.

The values of PPR_{ETR} were highest from May to August; however, while diatoms occupied 54.0% of the total phytoplankton biomass during the whole sampling period, flagellates (dinoflagellates, raphidophytes and silicoflagellates, including the harmful species) accounted for 76.4% in May through August. From May to July, a harmful silicoflagellates, *Vicicitus globosus*, dominated (more than 30% of the total phytoplankton biomass). Another notorious fish killing raphidophytes, *Chattonella* spp., occupied 31.8% from May to August. Although a non-harmful dinoflagellate genus *Ceratium* was the most dominant group in dinoflagellates during this season, a harmful species *Karenia mikimotoi* was the second major dinoflagellate. The circumstances leading to harmful species to dominate over diatoms may not be favorable to coastal fisheries.

Chapter 3. Trials of sea-bottom plowing in Bingo-Nada

Sea-bottom plowings were conducted at sites off Tajiri Chou, Fukuyama, Hiroshima, in April and August 2015, or off Tomo Chou, Fukuyama, in June, July and August 2016 and 2017. Plowing gears, dredges for shrimp fishing (April 2015) or custom- made gears (other than April 2015), were pulled by small trawl fishery boats. The areas were 2.3 km^2 in April 2015, 0.8 km^2 in August 2015 and 1.5 km^2 in 2016 and 2017. In the most cases, alterations of the bottom sediment from reductive to oxidative condition were observed, as indicated by increased ORP values and lowered sulfide levels.

The additional effect, to increase diatom population in the water column by resuspending the resting stage cells, were also achieved. Within a week after the plowing, diatoms increased significantly. At the sites, 90% of the resting stage cells of diatoms consisted of genera *Skeletonema*, *Chaetoceros*, and *Thalassiosira*, and these vegetative cells were actually the major components. For an instance, the case in August 2015 showed three genera increased from 278 ± 355 cells mL^{-1} to 1202 ± 1044 cells mL^{-1} in one day after the plowing.

In the cased of August 2016, diatoms also increased, from 734 ± 296 cells mL^{-1} to 1635 ± 138 cells mL^{-1} immediately after the plowing. Along with this increase of diatoms, PPR_{ETR} increased twice as higher as before the plowing. This result insisted plowings temporarily might improve primary productivity with increase of diatoms.

Chapter 4. General discussion

Based on Chapter 2, possible mechanisms those may hinder primary production at Bingo-Nada were assumed. Most prominent character was notable diatom blooms in January, and such winter diatom blooms apparently caused unfavorable phenomenon for the subsequent seasons. Dense diatom occurrences consume large amount of inorganic nutrients, and in conjugation with low precipitation continuing from November until May, the blooms accelerate insufficiency of the nutrients, those eventually resulted in absence of “spring diatom bloom” which should be typically found in temperate coasts. The following season, May to August, exhibited the highest primary production rate; however, the facts that various flagellate taxon (dinoflagellates, raphidophytes and silicoflagellates) achieved 76.4% of the total phytoplankton biomass during this period, and that the fish killing species (*V. globosus*, *Chattonella* spp., and *K. mikimotoi*) accounted 53.5% of them, might not be favorable for the coastal fisheries. Significant turbidity in the autumn again caused drops of the primary productivity. In conclusion, senescence of the important primary producers, diatoms, that continued almost whole year except winter season might be a primal factor hindering the primary productivity at the site.

To change growth phases of diatom, appropriate amount of inorganic nutrients must be supplied especially after the winter season, which is however currently infeasible. Instead, as describing in Chapter 3, the sea-bottom plowing is one of the countermeasures to increase diatom’s production, which could be done by fishermen themselves. Most notable findings in this study were diatom stimulation as well as improving primary productivity. Such activities involving fishermen as well as municipal participation are now needed to bottom up the primary productivity and further expecting restoration of the Inland fisheries.