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Oligotrophication and its measures in the Seto Inland Sea, Japan

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Abstract: The Seto Inland Sea experienced eutrophication during the period of high economic growth and then subsequent oligotrophication due to reduction of inflow load. The nutrient concentration in the seawater peaked in the beginning of 1970's, and thereafter, it has been decreasing. Dissolved inorganic nitrogen (DIN) has remarkably decreased in recent years following the decrease in dissolved inorganic phosphorus (DIP). As a result, Nori (*Pyropia*) production has decreased in recent years due to bleaching of leaves caused by DIN deficiency. Recent slack in fisheries production was also likely influenced by the nutrient depletion as evidenced by the fish catch using a compact trawl. The process of both eutrophication and oligotrophication that occurred in the Seto Inland Sea can be explained by hysteresis. We introduce several countermeasures to the oligotrophication in the Seto Inland Sea. In particular, to improve Nori production, local nutrient supply was experimentally augmented, such as by application of fertilizer, temporary discharge of dam water, sediment plowing, and ad hoc operations of relaxing sewage treatment water.

Key words: fisheries production, nutrient, oligotrophication, Seto Inland Sea

Introduction

The Seto Inland Sea had been known as a beautiful and bountiful sea with a rich ecosystem. However, during the period of high economic growth, eutrophication progressed, and fishery damage caused by harmful algal blooms became frequent. Since the Interim Measures Law concerning Conservation of the Environment of the Seto Inland Sea (later the Special Measures Law) was enacted in 1973, the water quality of the Seto Inland Sea has improved by a series of measures such as reduction of inflow load. On the other hand, oligotrophication has become a problem in recent years (Yamamoto, 2003), and it caused a decrease in Nori (*Pyropia*) production due to bleaching of leaves because of nutrient depletion (Murayama *et al*., 2015; Tada *et al*., 2010). In addition, it is also pointed out that the decrease in fisheries production, such as small pelagic fish and demersal fish, is related to nutrient reduction (Tanda and Harada, 2012). Here, we describe the changes in and current situation of water quality in the Seto Inland Sea and discuss the influence of load reduction on the lower trophic ecosystem and fishery production. We also introduce nutrient supply methods, which were experimentally conducted as countermeasures for bleaching Nori.

Variation of water quality

Fisheries research institutions surrounding the Seto Inland Sea have been monitoring the monthly water quality since 1973. The monitoring has been carried out using similar methods over time, and it can elucidate the process of cultural oligotrophication in the Seto Inland Sea. **Fig.1** shows the variations of annual averaged concentrations of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) in the surface layer of the Seto Inland Sea. The DIN concentration was extremely high in the 1970s, decreased sharply in the 1980s, and then remained flat. After that, it decreased again in the latter half of

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the 1990s and remains at low levels in recent years. According to the pollutant discharge loads in the Seto Inland Sea (**Fig.2**), the load of chemical oxygen demand (COD) sharply decreased in the latter half of the 1970s, and the load of total nitrogen (TN) decreased after the latter half of the 1990s, which is in good agreement with the decreasing period of the DIN concentration. On the other hand, the DIP concentration remained flat after decreasing until the early 1980s. The load of total phosphorus (TP) has sharply decreased in the first half of the 1980s following reduction of the load of COD in the latter half of the 1970s, which is consistent with the decreasing DIP concentration. However, there was no decrease in DIP concentration corresponding to the TP load reduction in the early 2000s.

Regarding water quality in each sub-area (**Fig.3**), DIN started to decrease in the 1980s in the western part, then it tended to decrease in the 1990s in the eastern and central parts of the Seto Inland Sea. The decreasing rate of DIN concentration in the surface layer of each sub-area was 0.16 to 0.26 μM per year, but it was largest in the eastern part, Osaka Bay and Harima Nada (Abo *et al*., 2018). On the other hand, the DIP concentration had no large variation over the entire Seto Inland Sea, but the molar ratio of DIN and DIP has changed from 16 - 17 to 8 - 10 in the past 30 years, i.e., it has changed from a value close to the Redfield ratio to nitrogen deficiency (Tanda *et al*., 2014).

Variation of fisheries production

Recently, fisheries production in the Seto Inland Sea has been stagnant. Especially for Nori (*Pyropia*) culture, the influence of nutrient deficiency due to cultural oligotrophication is crucial to production. The annual production of Nori in the Seto Inland Sea increased in 1970s due to the maturation of the aquaculture technology and reached 4 billion sheets in the 1980s. In the 1990s, it remained at more than 3.5 billion sheets. However, it decreased sharply in the 2000s and has been around 2 billion sheets in recent years (**Fig.4**). The sharp decrease in the Nori production after 2000 coincided with the decrease in DIN concentration mentioned above. Since the late 1990s, bleaching of Nori leaves caused by nitrogen

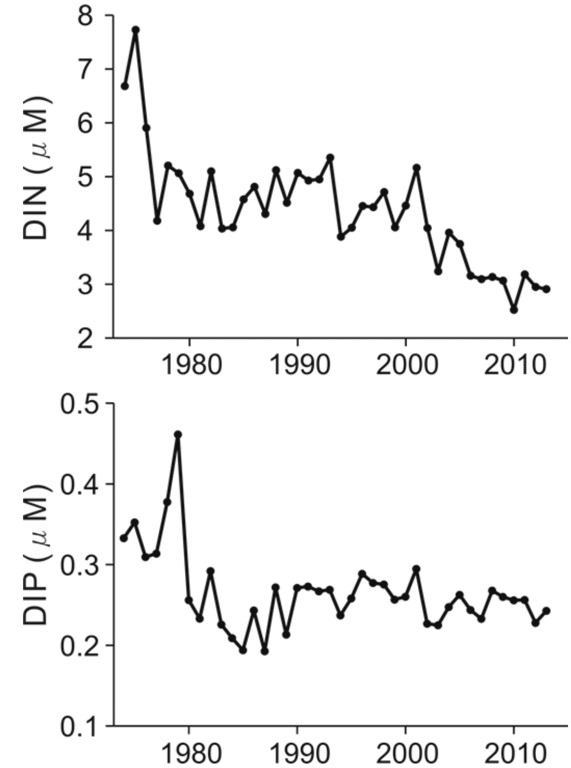

Fig. 1. Temporal variations in annual averaged concentration of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) in the surface layer of the Seto Inland Sea, Japan.

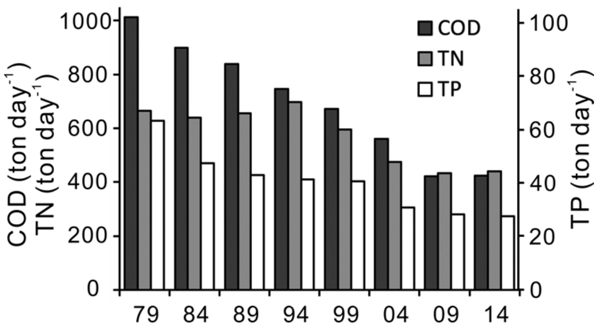

Fig. 2. Five-year changes in the generated loads of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) flowing into the Seto Inland Sea, Japan.

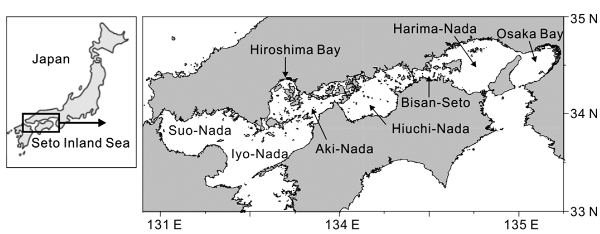

Fig. 3. Map of the Seto Inland Sea and sub-areas.

depletion occurred frequently. The bleaching of Nori leaves is said to occur at DIN concentrations of 3 μM or less in the eastern part of the Seto Inland Sea (Murayama *et al*., 2015). DIN deficiency is the main cause of the recent decrease of Nori production, but global warming may also cause a decrease in Nori production because water temperature rise could have shortened the culture period.

The fish catch of the Seto Inland Sea peaked in the beginning of the 1980s, but the catch in 2014 was less than 160,000 tons, which is one third of the peak production (Fig.5). The cause of the catch decline is not clear. Although land reclamation during the rapid economic growth period in Japan and overfishing could be responsible for the decrease in fish catch, oligotrophication is pointed out as a decisive factor in the decrease in fishery production. Tanda and Harada (2012) revealed that fluctuations in catch of sand lance *Ammodytes personatus* in Harima-Nada in the eastern part of Seto Inland Sea synchronized with fluctuations in the DIN concentration, with 2-3 years lag. There was also a tight relationship between 0-year-old sand lance and DIN concentration. From these analyses, they concluded that nutrient depletion affected early survival and growth of sand lance larva. Tarutani and Nakajima (2011) showed the correlation between pollutant discharge load and the catch of demersal fish and shellfish in Osaka Bay. They also suggested bottom-up material flow may play a role in recent decreases in fisheries production in Harima-Nada.

As for Nori, which requires nutrients for growth, reduction of nutrient load directly contributes to the decrease in production. As coastal ecosystems are largely affected by various human disturbances (Jackson *et. al*, 2001), it is important to clarify the processes occurring in the ecosystem scientifically.

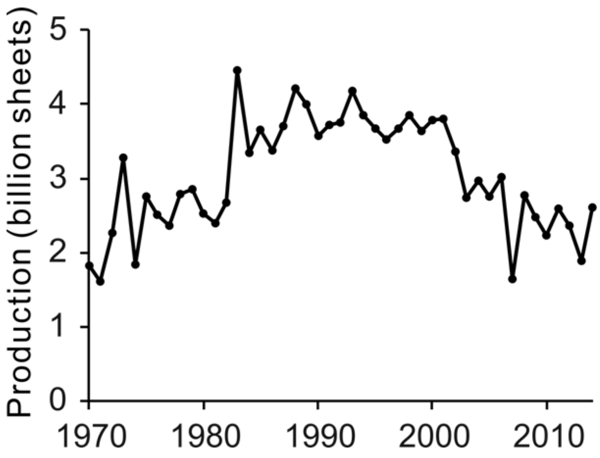

Fig. 4. Annual variation of Nori (*Pyropia*) production in the Seto Inland Sea, Japan.

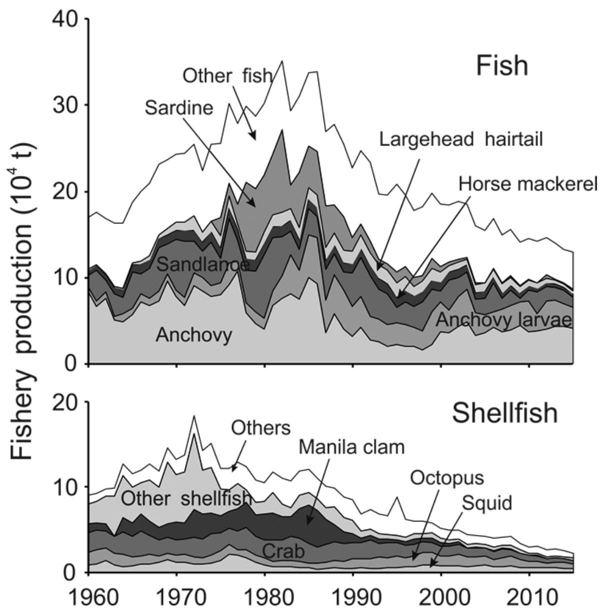

Fig. 5. Annual variations of fish catch (upper) and shellfish production (lower) in the Seto Inland Sea, Japan.

Processes of eutrophication and oligotrophication

Along with the eutrophication and oligotrophication that occurred in the Seto Inland Sea, hysteresis was observed (Yamamoto, 2015). The pattern of increased fisheries production during eutrophication was different from that during oligotrophication (Fig.6). Although fisheries production should return to the original position at the end of oligotrophication process, as mentioned theoretically by Scheffer (1989), fisheries production in the Seto Inland Sea did not return to the original position; it decreased to a much lower level (Fig.6). Ecosystem structure might have changed or overfishing may be a cause. The cause of this issue is still under debate and remains to be solved.

Practical measures against oligotrophication

In the Seto Inland Sea, experimental attempts to supply nutrients to fishing grounds have been made as a measure against the oligotrophication. Especially to prevent the bleaching of Nori laver, fertilizer application, temporary discharge of dam water, relaxing discharge of sewage treatment water, etc., were carried out. A fundamental issue that is common to these techniques is the diffusion feature of seawater in the sea. Once we apply one of these techniques, added nutrient is diluted in a short time. For example, relaxing the discharge of sewage treatment water has been conducted to increase DIN concentration in the treated water to the allowable levels by suppressing denitrification and/or nitrification processes, with restriction during the winter Nori growing season. Evaluation by numerical simulation reproduced the dispersion pattern of a high nutrient water mass to the Nori cultivation area, which was monitored by field observations (Abo *et al*., 2012; Harada *et al*., 2018).

In order to sustain fisheries production in the oligotrophic Seto Inland Sea, effective measures may be different in each sub-area because of differences in terms of geography, oceanography, fisheries activity, and other social backgrounds. Even in the totally oligotrophic state it is in, oxygen depletion in the bottom water and/or harmful algal blooms occur in some sub-areas. Therefore, different measures applicable to each different sub-area are required. Furthermore, ideal water quality could be different among various stakeholders; some might desire higher water transparency, while others might desire high fisheries production. We, therefore, need an organization or council with various stakeholders representing different standpoints in each sub-area.

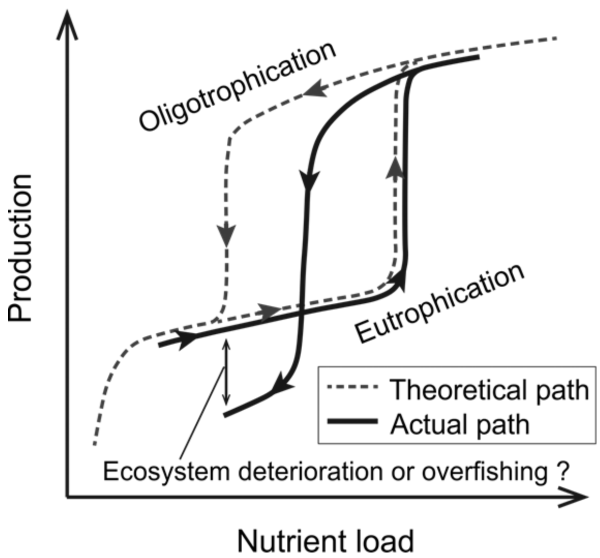

Fig. 6. The theoretical path and the actual path observed in the Seto Inland Sea as an example of hysteresis.

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The long-term variations in water quality in the Seto Inland Sea were investigated based on the routine observation data of the local fisheries experimental stations. The water temperature increased due to the global warming and the nutrient decreased due to oligotrophication. The reduction of DIN and DIP concentrations were largely affected by land load reduction.

(2) Abo K., Tarutani K., Harada K., Miyahara K., Nakayama A., and Yagi H., 2012: Effects of nutrient discharge on Nori aquaculture area in Kako River estuary. *J. JSCE, Ser.B2, Coast. Eng.*, **68 (2)**, I_1116-I_1120.

Effects of nutrient discharge on Nori aquaculture area were investigated. The Nori production in the winter season were sustained by nutrient discharge from the river, sewage treatment plant and industrial effluent. A numerical simulation evaluated the effects of nutrient control operation of the sewage treatment plant on the nutrient environments of the aquaculture area.

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This was the first study showing the Seto Inland Sea was in the state of ‘cultural oligotrophication’ caused by the reduction of nutrient loading. This study indicated that the measures to reduce phosphorus had caused a change in phytoplankton species composition, thereby altering the food web structure, suggesting that this might be the major cause of the reduction of fishery production.

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A numerical model was constructed to elucidate whether phytoplankton species diversity could be increased by an environmental fluctuation such as a pulsed nutrient supply. Diatom showed large fluctuations in cell density in response to pulses of nutrients, while dinoflagellate showed preference for continuous nutrient supply mode. Dam construction, which is one of the causes of oligotrophication, usually flattens variability in the freshwater discharge, hence lead to dinoflagellate dominancy.

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This study proposed measures for sustainable fishery production in an oligotrophic bay (Mitsu Bay). Water quality was extremely good (oligotrophic), therefore improvement of sediment quality was necessary. As oyster cultivation was popular in this bay, improvement of sediment quality using oyster shells could contribute to the formation of a recycling-oriented society.