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Société franco-japonaise d'Océanographie, Tokyo

Changes in nutrients and their effects on fisheries after the introduction of land-based nutrient loading regulations in the Seto Inland Sea since 1973: A review

Kuninao TADA[1, 2]*, Masatoshi NAKAKUNI[1], Hitomi YAMAGUCHI[1] and Kazhuhiko ICHIMI[1, 2]

Abstract: Nutrient decrease and their effects on fisheries in the Seto Inland Sea, Japan were discussed. It suffered from heavy eutrophication during Japan's period of high economic growth starting in the 1960s. At that time, red tides often occurred and fish culture was severely affected. Recently, water quality has dramatically improved. Although total nitrogen (TN) and total phosphorus (TP) runoff load from the land were reduced by 40% and 60%, respectively, TN and TP concentrations in seawater have apparently not decreased, despite the apparent nutrient concentration decrease. Nutrient decrease was not due to only nutrient runoff load from the land, and it was thought that nutrient release from the bottom sediment was also important. Despite the water quality improvement, fish catches have gradually decreased. Phytoplankton primary production did not response simply to nutrient decrease, and according to zooplankton, there is no data set to show their biomass variation. The conclusion is that the reason of fish catch decrease is still unknown. Whereas nutrient concentrations decreased, and presumably nutrient decrease will be a contributing factor, land reclamation, decreases in the area of tidal flats and algal/seagrass beds, global warming, and overfishing should be also thought as reasons contributing to fish catch decreases.

Keywords : *nutrient, Seto Inland Sea, phytoplankton, fish catch*

1. Introduction

The Seto Inland Sea is a large, enclosed sea in Japan (Fig. 1), known for its beautiful Mediterranean-style landscape and including about 600 islands. This sea is also an industrially developed area with about 30 million people living in the coastal area. During the period of high economic growth in Japan, beginning in the

1) Department of Applied Biological Sciences, Faculty of Agriculture, Kagawa University, Miki, Kita-Gun, Kagawa 761–0795, Japan
2) Aji Marine Station, Seto Inland Sea Regional Research Center, Kagawa University, Kamano, Aji, Takamatsu-City, Kagawa 761–0130, Japan

*Corresponding author: Kuninao Tada
Department of Applied Biological Sciences, Faculty of Agriculture, Kagawa University, Miki, Kagawa 761–0795, Japan
Tel: + 81–87–891–3148
Fax: + 81–87–891–3148
E-mail: tada.kuninao@kagawa-u.ac.jp

1960s, the Seto Inland Sea suffered from heavy eutrophication due to pollution with organic matter from industrial effluent and urban wastewater. At that time, red tides often occurred, and fish culture was heavily affected. In 1972, the *Chattonella antiqua* red tide that occurred in Harima Nada, the eastern part of the Seto Inland Sea, caused a catastrophic mass mortality of 14 million cultured yellowtail (*Seriola quinqueradiata*) with a value then of about 7.1 billion Japanese yen (Okaichi, 2002).

To resolve the situation, "Law concerning Special Measures for Conservation of the Environment of the Seto Inland Sea" was enacted in 1973. Since then, under this law, industrial effluent and urban wastewater have been regulated by a "Fundamental Policy for Reduction of Total Pollution Load (FPRTPL)" which requires that chemical oxygen demand and total nitrogen and phosphorus loading from the land surrounding the Seto Inland Sea must decrease by scheduled amounts every five years. Subsequently, the number of red tide occurrences decreased from 300 times to 100 times per year and is now consistently below 100 times annually (Imai *et al*., 2006). The environmental condition of the Seto Inland Sea is already well documented (Okaichi and Yanagi, 1997; International EMECS Center, 2008). Recent situations of marine environment and fisheries were also well documented (Central Environmental Council, 2021; Japan Fisheries Science and Technology Association, 2017; Abo and Yamamoto, 2019).

Although water quality has improved and nutrient concentrations of seawater decreased (Abo *et al*., 2018), recently commercial culture of *Pyropia* sp. (widely known by its Japanese name 'nori') has often suffered from bleaching due to lack of nutrient and, consequently, nori culture in the eastern part of the Seto Inland Sea has suffered from heavy losses in both annual yield (Japanese yen) and production (tonne or production number) (Matsuoka *et al*., 2005; Hori *et al*., 2008 ; Tada *et al*., 2010; Abo and Yamamoto, 2019). Fish catches, too, have gradually been decreasing (Tanda *et al*., 2014; Abo, 2016). Yamamoto (2003) had already reported on the oligotrophic condition of the Seto Inland Sea.

The present paper reviews changes in water quality of the Seto Inland Sea over the last 50 years and addresses the recent decrease in nutrient content, partly focusing on Harima Nada (Fig. 1), based on information obtained during previous studies (Nishikawa *et al*., 2010; Abo *et al*., 2018). Nutrient dynamics, phytoplankton biomass, primary production and fish catch decrease are also reviewed (cf. Tanda *et al*., 2014; Abo *et al*., 2016; Tada *et al*., 2014; Tada *et al.*, 2018; Nishijima *et al*., 2018; Nishijima *et al*., 2019).

2021 was the start of the United Nations Decade of Ocean Science for Sustainable Development (UNDOS), which lists seven social outcomes for an ocean that is clean, healthy and resilient, predicted, safe, sustainably harvested and productive, inspiring and engaging, with transparent and accessible data and technology (Intergovernmental Oceanographic Commission, 2020). The present study is in line with the basic policy of "a clean ocean" and is also concerned with ensuring a "sustainably harvested and productive" ocean (The united nations decade of ocean science for sustainable development (2021–2030)) (UNESCO-IOC, 2021). It falls within the UN Sustainable Development Goal (SDG) no. 14, to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" (United Nations, 2015).

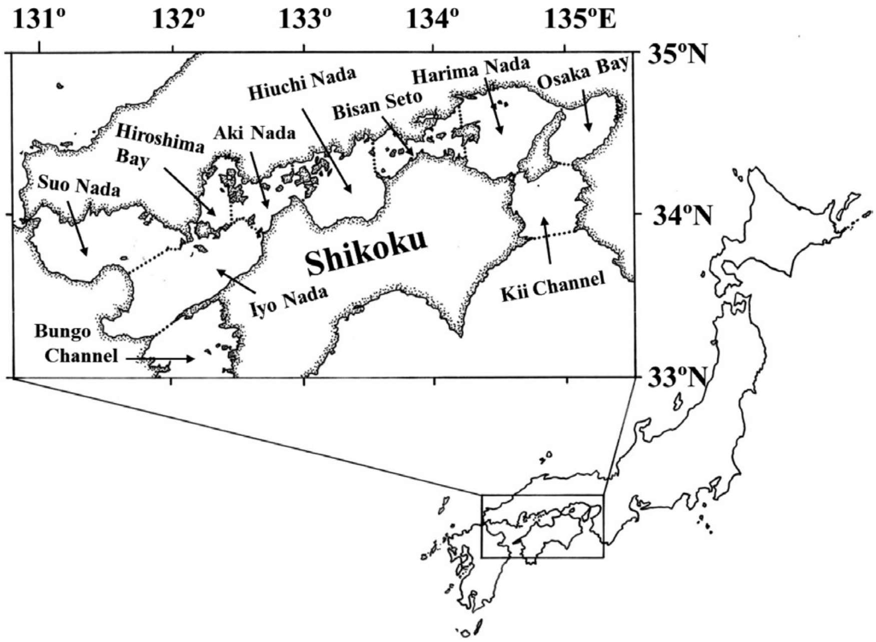

Fig. 1 Location of the Seto Inland Sea, which is composed of the sea areas known as Suo Nada, Iyo Nada, Bungo Channel, Hiroshima Bay, Aki Nada, Hiuchi Nada, Bisan Seto, Harima Nada and Osaka Bay from West to East.

2. The decrease of nutrient concentrations and its dynamics

2.1 The decrease of nutrient concentration

Nutrient concentrations (NO_3, NH_4, and PO_4) in the Seto Inland Sea have apparently decreased since the 1970s (TARUTANI, 2007; NISHIKAWA *et al.*, 2010; TANDA *et al.*, 2014; ABO *et al.*, 2018). For example, since 1983, dissolved inorganic nitrogen (DIN: NO_3 + NO_2 + NH_4) concentrations in surface seawater have decreased every decade in almost all parts of the Seto Inland Sea (Fig. 2). Since 2002, nori culture has been particularly heavily damaged in the eastern part of the sea due to a lack of nutrients, because nori growth is directly influenced by nutrient concentrations (TADA *et al.*, 2010). Note that the amounts of total nitrogen (TN) and total phosphorus (TP) run-off load from the land in the Seto Inland Sea were reduced by 40% and 60%, respectively, from 1979 to 2009 by implementation of the "FPRTPL" (Fig. 3): TP load was reduced from the 1980s, probably due to such policies as the use of phosphorus-free detergents; TN load showed a reduction only after the 1990s, and the reduction was predominant after 2000. However, TN and TP concentrations in seawater have shown no marked decrease and they were almost constant or slightly decrease. (Fig.4). These data suggest that the apparent decrease of nutrient concentrations cannot be explained only by reduction of TN and TP loading from the land. In seawater, sum of DIN, DON (dissolved organic nitrogen) and PON (particulate organic nitrogen) are TN (DIN + DON + PON = TN). According to the DIN and TN, it was reported that the annual variations of TN concentration was large and did not show the certain trend, whereas DIN concentration was

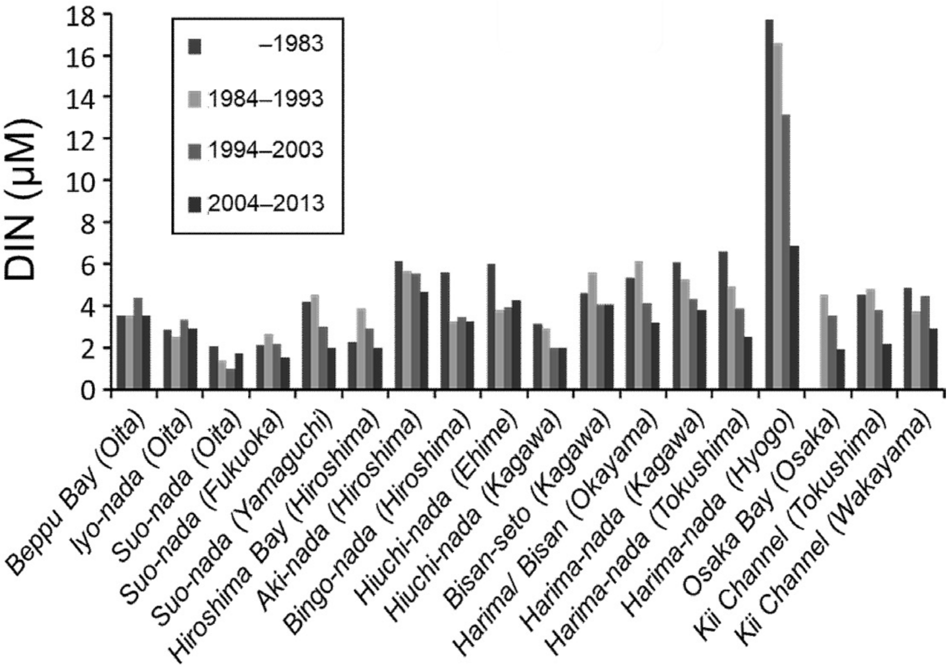

Fig. 2 Average DIN concentration per decade in different parts of the Seto Inland Sea reproduced from ABO *et al.* (2018) with the authors' permission. Names in parentheses are the associated Prefecture names.

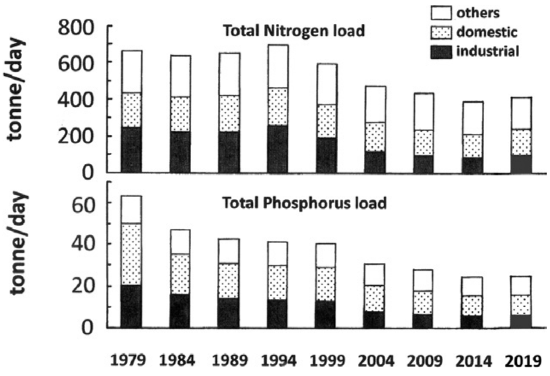

Fig. 3 Changes in the total nitrogen and phosphorus load in the Seto Inland Sea modified from CENTRAL ENVIRONMENTAL COUNCIL (2021); SETOUCHI NET, 2011a).

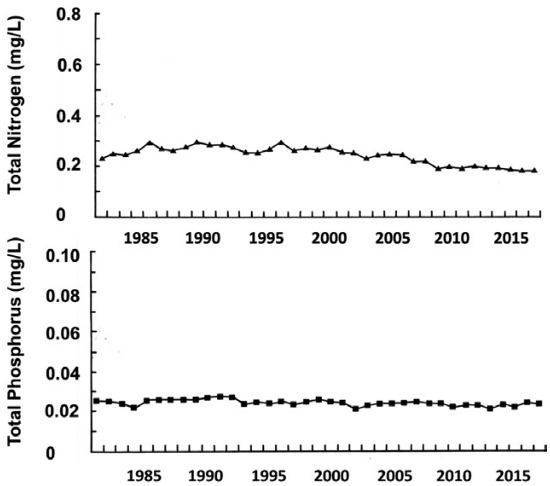

Fig. 4 Yearly changes in total nitrogen and phosphorus concentrations in the Seto Inland Sea (SETOUCHI NET, 2021b).

clearly decrease after 1990 (TADA *et al.*, 2010). KOBAYASHI *et al.* (2009) reported that the annual average ratios of DIN, DON and PON for TN in surface layer of Harima Nada were 0.22, 0.55 and 0.23, respectively, and the annual variation of DON concentration was smaller than those of

DIN and PON. Asahi *et al.* (2019) also reported similar results about for the seasonal average ratios of DIN and DON in surface seawater of the entire of the Seto Inland Sea. They also reported that DIN concentrations decreased from 1990 to 2010, whereas DON concentrations did not decrease.

2.2 Nutrient dynamics in the coastal waters of the Seto Inland Sea

To explain the observed nutrient conditions, it is necessary to understand the mechanism of nutrient circulation and fate. Nutrient concentration should be the result of a balance of nutrient inflow and outflow at three sites (Fig. 5a): freshwater inflow from rivers; the interface between inshore and offshore waters; and the interface between the bottom sediment and bottom water.

Surprisingly and unintuitively, more than half of the N and P content in the Seto Inland Sea originates in the Pacific Ocean (Fujiwara *et al.*, 1997; Yanagi and Ishii, 2004; Hayami *et al.*, 2004). Despite problems with methods to estimate the amount of ocean-origin nutrients in coastal seas, Takeoka (2006) considered that about 60% of N and P is of oceanic origin. Therefore, since TN and TP concentrations in Seto

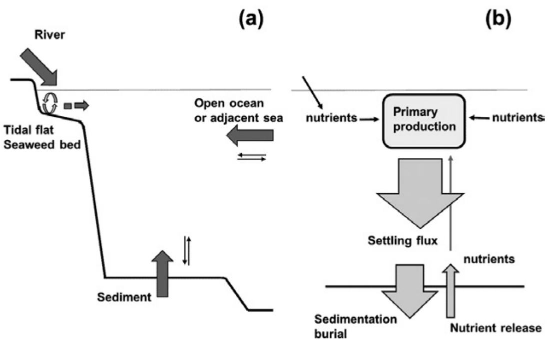

Fig. 5 Diagrams illustrating (a) nutrient supply, and (b) the nutrient cycle via phytoplankton primary production and bottom sediments in coastal waters (Tada, 2021).

Inland Sea seawater apparently have not decreased, despite the decrease in TN and TP runoff from the land, it seems that N and P load from the land is a much smaller fraction compared to the contribution from the open ocean and bottom sediment (Fig. 5a).

Among these three sources of nutrients, there have been few measurements of nutrient flux from bottom sediment in the coastal water in Japan including the Seto Inland Sea. Therefore, upward nutrient fluxes were monitored across the overlying water-sediment interface using the core incubation method. In Harima-nada, it was estimated that the DIN release flux from the sediment was 46.4 tonnes d^{-1} (Tada *et al.*, 2014). It is about 3.2 times larger than nutrient inflow from rivers, which was estimated at 14.5 tonnes d^{-1} (Yamamoto *et al.*, 1996). In this regard, this ratio changed depending on the coastal water body (Abo *et al.*, 2015).

DIN and $Si(OH)_4$ fluxes from bottom sediment were proportional to bottom sediment temperature in Tsuda Bay, which is a small bay adjacent to Harima-Nada (Tada *et al.*, 2014). The PO_4 flux was not measured. Nutrient flux measurements at 8 stations in Harima-Nada and Osaka Bay revealed that DIN fluxes were proportional to TN content in the surface sediment layer (0–1 cm) and bottom sediment temperature. From these results, DIN (NH_4) fluxes from bottom sediments are expressed by the following equations (Tada *et al.*, 2018).

$$NH_4 \text{ flux } (\text{mg m}^{-2} \text{d}^{-1}) = G_T \times (C_N - 1.301),$$
$$G_T = 1.8020 \times \exp(0.1277 \times T),$$

where C_N and T are TN content (mgN.g^{-1}) in surface sediment layer (0–1 cm) and bottom sediment temperature (℃), respectively. The results suggest that nutrient flux can be forecast simply by TN content and the temperature of

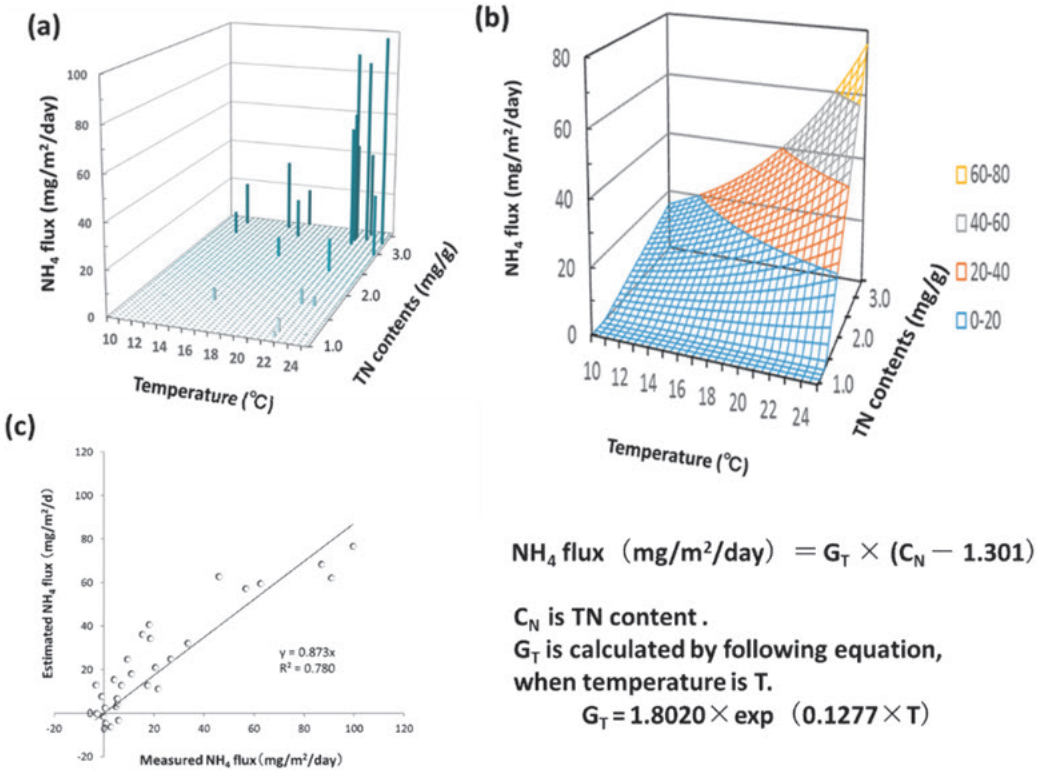

Fig. 6 (a) Relationship between NH_4 flux from bottom sediments, surface sediment temperature and TN content; (b) estimated upward NH_4 fluxes using the equation shown below; (c) relationship between measured fluxes and estimated fluxes (TADA *et al.*, 2018).

the surface sediment, although it is generally considered that nutrient upward flux depends on the sediment grain size (Fig. 6).

To further investigate the nutrient dynamics of the Seto Inland Sea, current research is attempting to calculate the budget of the nutrient cycle in the water column, including primary production by phytoplankton, organic matter settling fluxes, decomposition of settling matter in the bottom layer, and upward nutrient fluxes from bottom sediments (Fig. 5b).

3. Phytoplankton assemblage and primary production

3.1 Phytoplankton cell density and community composition

During the period of nutrient concentration decrease, long-term data sets of phytoplankton abundance in the Seto Inland Sea are rare. NISHIKAWA *et al.* (2010) demonstrated the nutrient and phytoplankton dynamics in Harima-Nada during a 35-year period from 1973 to 2007 (Fig. 7). They revealed that from the 1970s to the late 1990s, DIN decreased by half from about 10 μM to 5 μM. Before 1990, higher total cell densities were often observed. Recently, maximum cell densities rarely exceed 4,000 cells ml^{-1}, whereas this was often observed before 1990

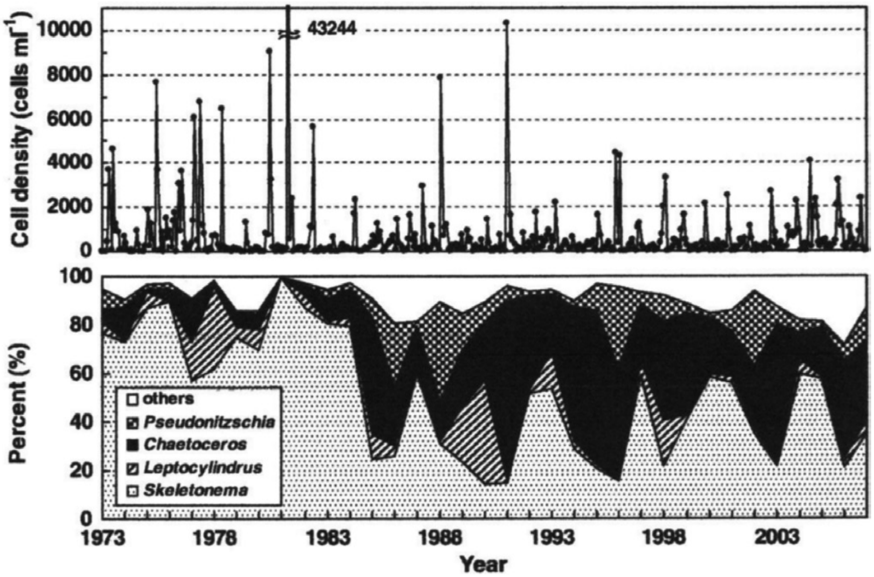

Fig. 7 Long-term variations in monthly total cell density and yearly percent species composition of diatoms in the surface layer of Harima-Nada, Seto Inland Sea, over the 35 years from 1973 to 2008 reproduced from NISHIKAWA *et al.* (2010) with the authors' permission.

(Fig. 7). Diatoms were the dominant phytoplankton group (> 90%) throughout this 35-year period and, interestingly, in the mid-1980s there was a dramatic shift from *Skeletonema* dominance (up to 70%) to *Chaetoceros*, which may be attributed to differences in the life cycle of *Skeletonema* and *Chaetoceros* and response to the decrease in DIN concentration.

3.2 Phytoplankton primary production

The ^{14}C (STEEMAN NIELSEN, 1952) and ^{13}C (HAMA *et al.*, 1983) methods for measuring the primary production of coastal waters have rarely been used in Japan, except for the study by TADA *et al.* (1998). Therefore, the long-term relationships between primary production and nutrient concentration were unknown. Recently, however, NISHIJIMA (2018, 2019) estimated primary production in the Seto Inland Sea and reported changes over an extended period: the distribution of Chl *a* concentration in autumn from 1980 to 1985 in the Seto Inland Sea is shown in Fig. 8. Concentrations higher than 10 μg L^{-1} of Chl *a* were located in Osaka Bay and the northern part of Hiroshima Bay, accounting for 6% of the total area of the Seto Inland Sea and these areas were defined as 'red tide' (TSUTSUMI *et al.*, 2005).

NISHIJIMA (2018, 2019) classified their monitoring sites into five groups, based on Chl *a* concentration in 1981 to 1985 (Fig. 8). They showed that the decrease in primary production was characteristic for each group. The group with Chl $a > 10$ μg L^{-1} in 1981 to 1985 showed a decrease in primary production of approximately 45%, much larger than the decrease of other group (Fig. 9). The decrease was only 14% in the groups with a Chl *a* lower than 10 μg L^{-1} in 1981 to 1985, but these groups cover 94% of the total area of the Seto Inland Sea. These results show clearly that the decrease in primary production since the 1980s did not occur uniformly

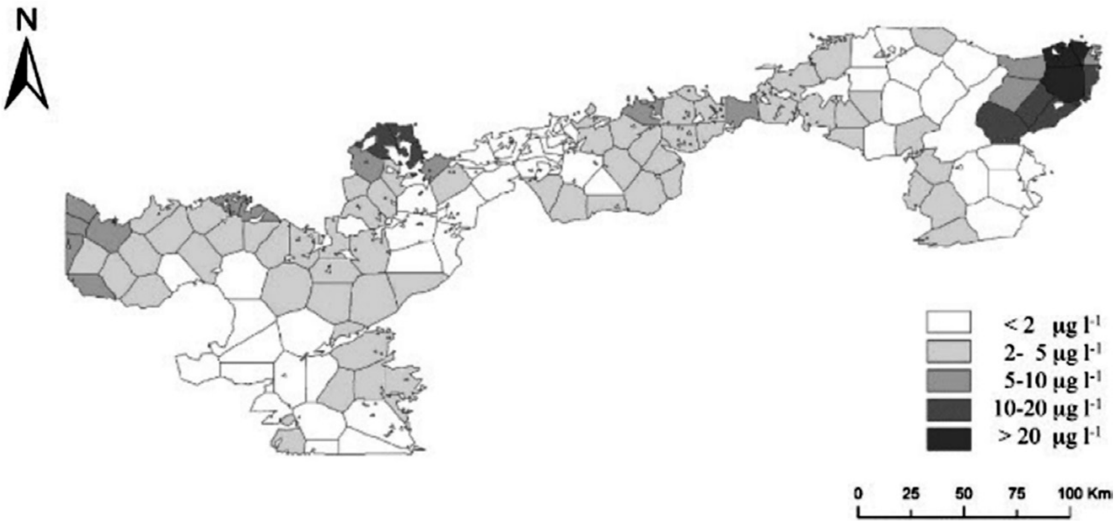

Fig. 8 Spatial distribution of mean autumn chlorophyll *a* concentration from 1980 to 1985 reproduced from NISHIJIMA (2018) with the authors' permission.

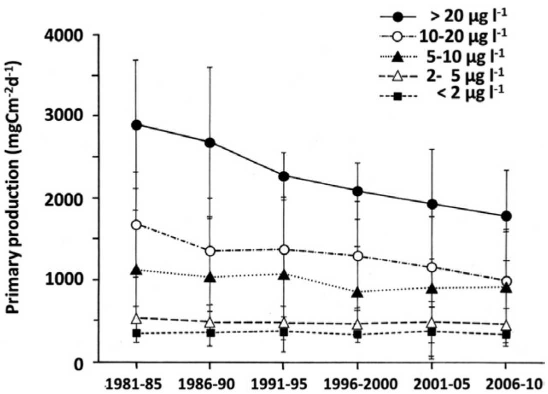

Fig. 9 Historical changes in primary production of each group classified by mean chlorophyll *a* concentration, from 1980 to 1985 reproduced from Nishijima (2018) with the authors' permission.

within the Seto Inland Sea, and the decrease was small in most areas (94%). The greatest decrease was observed in areas with a large urban watershed with high loading of nutrients and, conversely, a small decrease was observed in offshore areas with a low loading of nutrients. Their data suggested that phytoplankton primary production does not respond simply to nutrient decrease.

4. Decrease of Fish catches

Another current problem is the decrease of fish catches (ABO, 2016) (Fig. 10), which is thought to be related to the nutrient decrease (TANDA *et al.*, 2014). Fish catches were highest at the beginning of the 1980s, after which they decreased steadily. However, curiously, fish catches were high when red tide occurrence was also high (Fig. 10). Now, fish catches are lower than in the days when red tides occurred often, although water quality has improved. The relationships among fish catches, red tides and water nutrient content are thought to be as represented in Fig. 11. Before the period of high economic growth in Japan, water quality was good and biomass was high. At that time, the nutrient cycles were considered to be relatively simple and the ecosystem was productive. However, due to ensuing environmental degradation as the period of high economic growth progressed, water quality deteriorated, although fish catches did not decrease. In latter half of 1970s and first

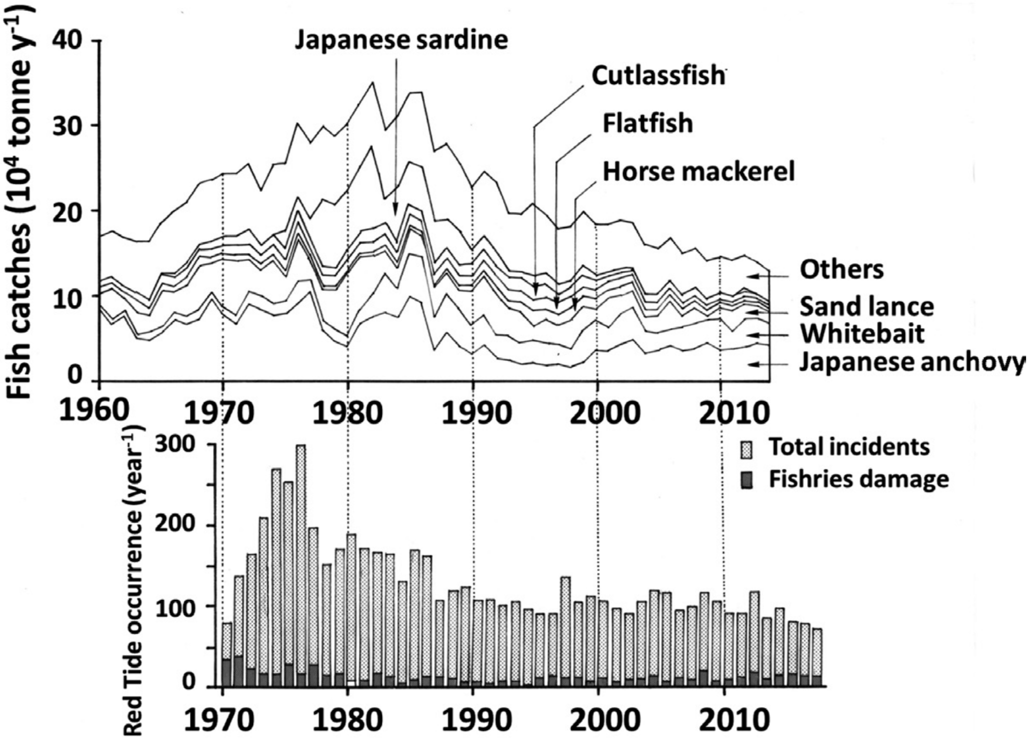

Fig. 10 Annual catches of different fish species, excluding fish culture modified from ABO (2016) and (below) the annual number of red tide occurrences (SETOUCHI NET, 2021c).

half of 1980s, Japanese sardine and Japanese anchovy catch was high and they were cheap, while expensive fish such as red sea bream were rare. Therefore, fish biodiversity was thought to be low, although biomass did not decrease. The aim of enacting "Law concerning Special Measures for Conservation of the Environment of the Seto Inland Sea", in 1973, was to recover the simple nutrient cycle and productive ecosystem. However, almost 50 years have passed but although water quality has improved, fish biomass has decreased. In Fig.11, the present status is at higher water quality but a biomass lower than in the 1970s.

In the Seto Inland Sea, the areas of tidal flat and algal/seagrass bed have decreased due to land reclamation (Fig. 12). Algal/seagrass beds are refuges for egg laying and aiding juvenile

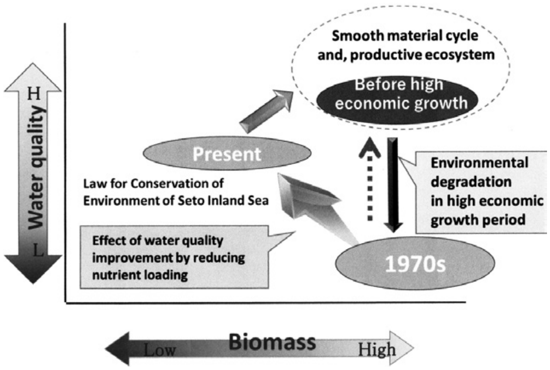

Fig. 11 Conceptual illustration of environmental conservation (modified from Ministry of the Environment; Conceptual representation of "Marine Healthy Plan 〔Project on the Normalization of Material Circulation in Coastal Marine Environment〕")

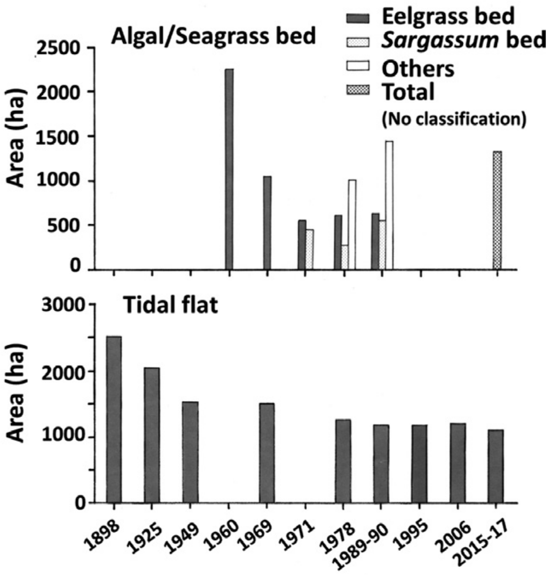

Fig. 12 Changes in area of algal/seagrass beds and tidal flat in the Seto Inland Sea modified from CENTRAL ENVIRONMENTAL COUNCIL (2021) and SETOUCHI NET (2021).

fish to resist predation until they reach adulthood. SHOJI *et al.* (2007) conducted the experiments in mesocosm to indicate that *Zostera marina* habitat reduces vulnerability of red sea bream juvenile from the predation by piscivorous fish, and seaweed bed increases the survival rate of the juveniles. Loss of such areas during the last 50 years may explain the currently low fish biomass, despite improvements in water quality. Overfishing also should be considered as a reason of fish catch decrease. For example, it was pointed out that fishing pressure was high for the Spanish Mackerel *Scomberomorus niphonius* and mud dab *Pleuronectes yokohamae* in the Seto Inland Sea (NAGAI *et al.*, 1996; NAGAI, 2003; IMOTO *et al.*, 2007).

It seems, then, that improvement of water quality alone does not guarantee a sustainable harvest and a productive coastal ecosystem. The reason for the fish catch decrease is still uncertain. As described above, phytoplankton primary production did not respond simply to the nutrient decrease, and there is no time series of data available for zooplankton production in this sea, so the relationships among coastal nutrients, phytoplankton, zooplankton and fishes are unclear. Moreover, the increase in water temperature associated with global warming induces changes in fish fauna. For example, recently the impact of warming on the physiological condition of ridged-eye flounder *Pleuronichthys lighti* in the central part of Seto Inland Sea was reported (YAMAMOTO *et al.*, 2020). Presumably land reclamation, the decrease in areas of tidal flat and algal/seagrass beds, global warming and overfishing are all reasons for fish catch decreases, but the contribution of nutrient decrease is still unclear. However, some fishes have increased in the Seto Inland Sea, despite of nutrient decrease. YAMAMOTO *et al.* (2019) revealed that red sea bream *Pagrus major* catch has increased from 297 tons in 1972 to 2,039 tons in 2010 in eastern Seto Inland Sea.

5. Conclusion

Nutrient concentrations apparently have decreased over the last 50 years in almost all parts of the Seto Inland Sea but TN and TP concentrations in the seawater have remained almost constant or slightly decrease. Nutrient release from the bottom sediment has been shown to be larger than nutrient loading from the land runoff during the summer period in Harima-Nada. Unfortunately, there are few data sets providing comparative information on previous nutrient fluxes from bottom sediment. Fish catches also gradually decreased after the 1980s but the reasons for this are unclear. However, clearly, poor nori harvest is directly related to a lack of nutrients. Phytoplankton primary production does not respond simply to nutrient decrease. Substantial phytoplankton production decrease was only observed at a very small part (6% of the total area) of the Seto Inland Sea, and there was only a marginal decrease in most areas (94%), despite nutrient decrease in all parts of this sea. The conclusion is that the reason of fish catch decrease is still unknown. Whereas nutrient concentrations decreased and presumably nutrient decrease will be a contributing factor, land reclamation, decreases in the area of tidal flats and algal/seagrass beds, global warming, and overfishing should be thought as reasons contributing to fish catch decreases.

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