3 Oligotrophication in the Seto Inland Sea

Tetsuo Yanagi

Abstract

Over the past 50 years, the Seto Inland Sea has experienced both eutrophication and oligotrophication. In terms of year-to-year variation, the relationship between the phosphorus load and the number of occurrences of red tides shows a clockwise hysteresis, while that between nutrient concentration and fish catch has a counterclockwise hysteresis. Such a difference is the result of the mutual interaction between the water quality and bottom sediment, that is, the organic matter accumulated in the bottom sediment during the period of eutrophication. Therefore, the number of red tides during the period of oligotrophication is greater than during eutrophication at the same phosphorus load due to the release of dissolved inorganic phosphorus from the bottom sediment. The fish catch during oligotrophication is less than during eutrophication at the same nutrient concentration due to the generation of hypoxia in the bottom layer during the stratification period.

Keywords

Eutrophication • Oligotrophication • Interaction between water quality and sediment • Hysteresis

3.1 Introduction

Since ancient times, people have enjoyed the Seto Inland Sea, one of the most beautiful seas not just in Japan but in the world. It is blessed with numerous islands, a mild climate, low precipitation, and abundant nature (Fig. 3.1). The Seto Inland Sea is the largest semi-enclosed coastal sea in Japan and is surrounded by three large islands, Honshu, Kyushu, and Shikoku, with more than 700 smaller islands within its area. The total shoreline is 6,868 km in length (Fig. 3.2). It is about 450 km from east to west and varies from 15 to 55 km north to south. It has an area of 23,203 km^2 with an average depth of 38 m. Accordingly, the volume of the Seto Inland Sea is approximately 881.5 km^3. The sea has many large and small straits, bays, and basins (“nadas” in Japanese). The Kii Channel (in the east) and the Bungo Channel (in the west) lie between the Seto Inland Sea and the Pacific Ocean, while the Kanmon Strait (in the west) lies between the Seto Inland Sea and the Japan Sea.

Except for Beppu Bay, Iyo-Nada, the Bungo Channel, Kii Channel, and Hibiki-Nada, almost all bays and nadas in the Seto Inland Sea are shallow and less than 40 m in depth (Fig. 3.3).

In this region, the annual average temperature and precipitation are 15 °C and 1,000–1,600 mm, respectively. This means that the region is relatively mild (low levels of precipitation and a narrow annual range of air temperature and humidity) in comparison with other regions in Japan. However, the mountainous areas around the Seto Inland Sea have greater precipitation with an annual rainfall of 2,000–3,000 mm. The amount of water discharged into the Seto Inland Sea from 669 river systems is as much as 50 billion m^3 a year.

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Through all seasons, the wind direction in the coastal areas is normally against the shoreline as a land-sea breeze develops. On the other hand, the wind direction in land areas largely depends on their individual geographical features. The wind pattern in the Seto Inland Sea is characterized by its regularity.

The seasonal variation in water temperature and salinity in the Seto Inland Sea is greater than that of the Pacific Ocean because the condition of the water in the Seto Inland Sea is generally affected by weather conditions.

Fig. 3.1 Landscape view of the Seto Inland Sea (Photo provided by the Seto Inland Sea Conservation Association)

Water is exchanged between the Pacific Ocean and the Seto Inland Sea through the Kii Channel and the Bungo Channel, while between the Japan Sea and the Seto Inland Sea it is through the Kanmon Strait.

Maximum tidal range in the Seto Inland Sea is about 3 m in the spring tide and the tidal current in narrow straits, such as the Naruto and Hayasui Straits, is fast and complex and reaches 5–10 knots. Complex geographical features affect the unique characteristics of the tide and tidal current in the Seto Inland Sea.

3.2 Changes in the Environment

3.2.1 Population

The watershed area of the Seto Inland Sea spreads out over about 68,000 km^2, which corresponds to 18 % of the total land area of Japan. The population of the area is about 35 million or about 28 % of the total population of Japan, and its annual specific rate of increasing has been around 2.8 % which is similar to the average for Japan as a whole (see Fig. 3.4).

Further, as shown in Fig. 3.5, the population density is 643 persons/km^2, which is 1.6 times greater than the average for Japan at about 340 persons/km^2. This means that the population is highly concentrated in this area, especially in Osaka Prefecture, with Fukuoka Prefecture coming next.

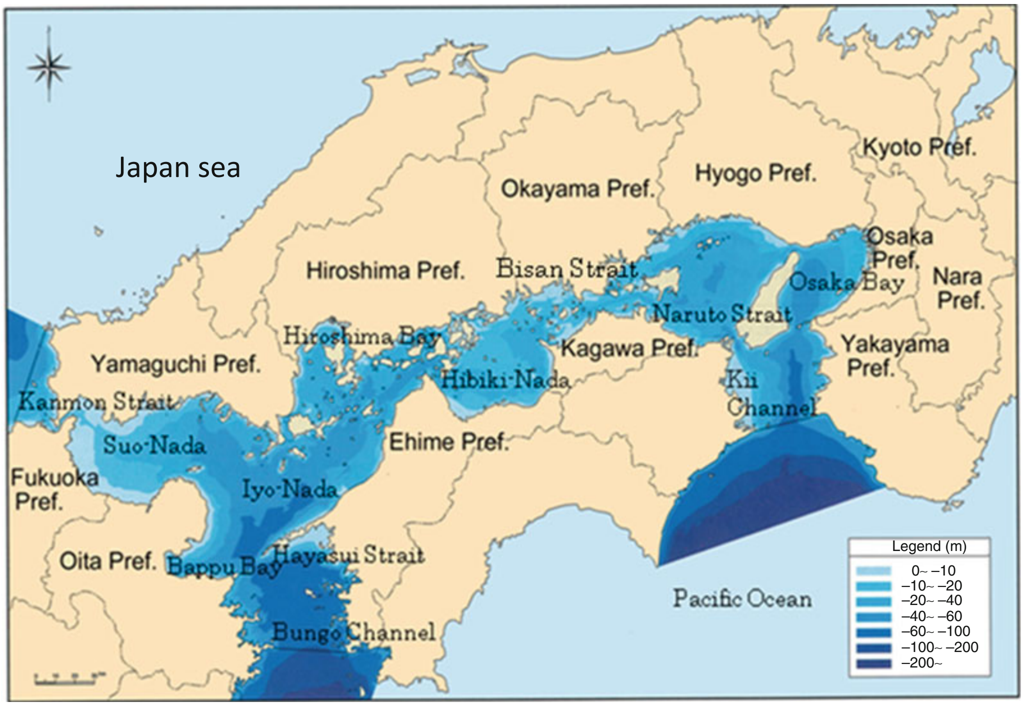


Fig. 3.2 Bays, nadas, straits, and channels in the Seto Inland Sea

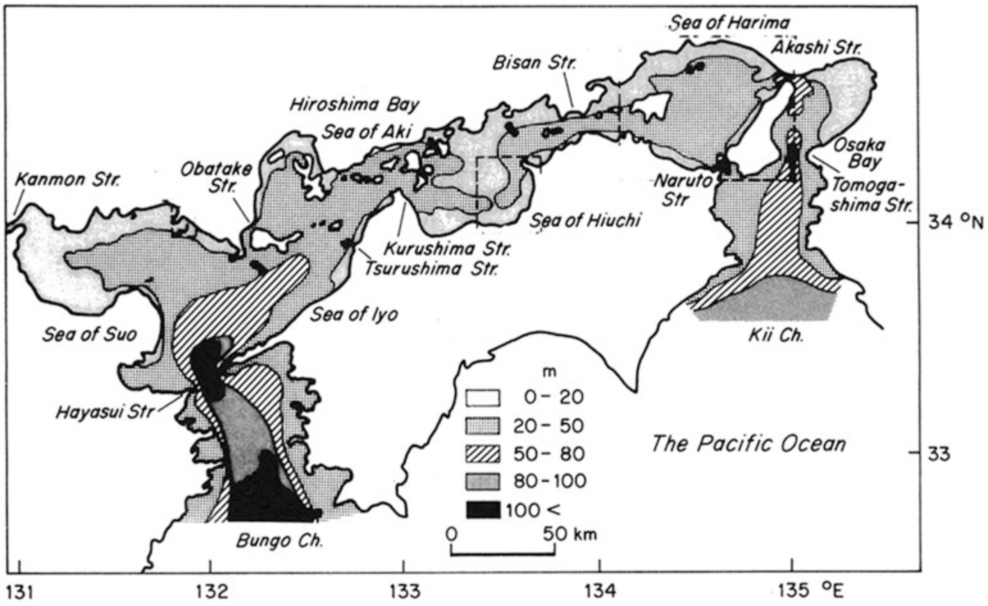


Fig. 3.3 Water depth in the Seto Inland Sea

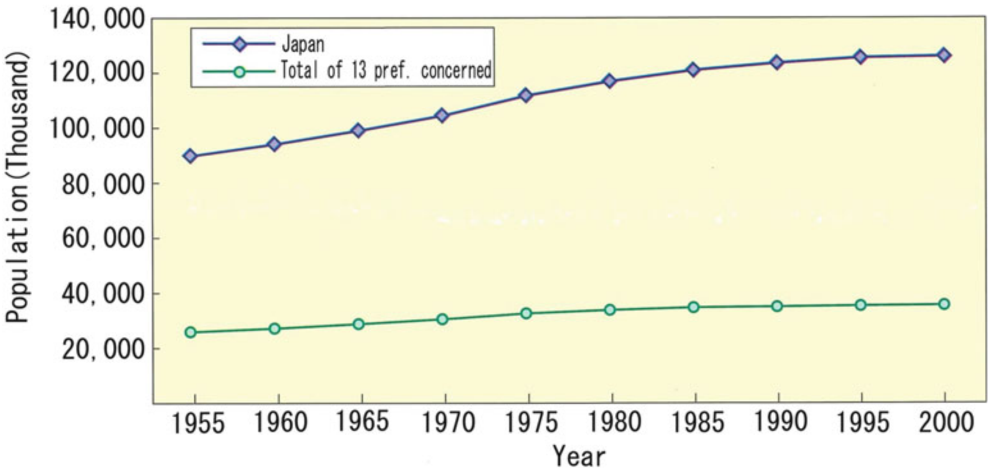


Fig. 3.4 Population of Japan as a whole and of the prefectures located in the watershed area of the Seto Inland Sea

3.2.2 Industry

The gross product of the 13 prefectures around the Seto Inland Sea was 129.8 trillion yen in 2002. The gross product from 1965 to 1995 had increased steadily, with an annual rate of increase of about 6.53 %. However, since 1996 the increase has not been very distinct and the level of production has become reasonably constant (Fig. 3.6).

With respect to the composition of industry in 1965, primary industries accounted for 7.4 % of the total, secondary industries represented 40.0 %, and tertiary industries 52.6 %. From 1965 to 1995, the ratio of secondary industries decreased by 7.3 %, while tertiary industries increased by 13.6 %, and this trend has not changed very much since then. The ratio in 2002, for example, was 0.85 % for primary, 25.3 % for secondary, and 73.8 % for tertiary industries.

The Seto Inland Sea offers advantageous conditions for industrial development, such as long shallow coasts suitable for reclaiming land for construction of factories and a population of some 30 million people living along the coastal areas. In the period of rapid economic growth of the 1960s and 1970s, heavy and chemical manufacturing industries grew up around the Seto Inland Sea, responding to the national government's "Income Doubling Plan". The construction of factories rapidly increased in the latter half of the 1960s after the New Industry City Law was enacted in 1963. At present, manufacturing industries in the area account for more than 30 % of the total production capacity for Japan.

Fig. 3.5 Population density of each prefecture in the watershed area of the Seto Inland Sea (Source: Survey conducted by the Association for the Environmental Conservation of the Seto Inland Sea)

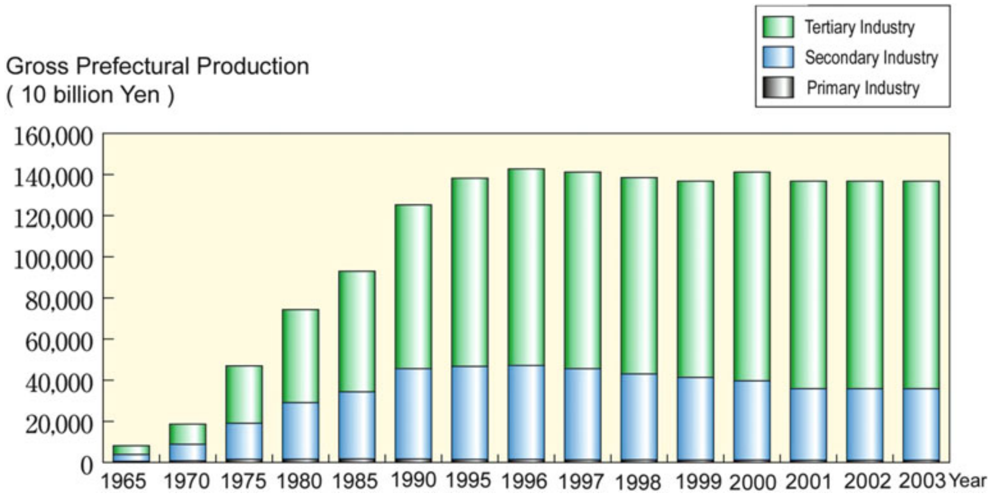


Fig. 3.6 Trends in and ratio of gross product in the 13 prefectures around the Seto Inland Sea (Source: Census for fiscal year of 2005)

There are basic manufacturing industries such as steel, oil refinery, and petrochemical industries in 13 prefectures around the Seto Inland Sea as shown in Fig. 3.7.

Trends in total shipping are shown in Fig. 3.8. The volume of shipping in this area has increased up to 1990, but since then it has changed and become rather stable. This trend is similar to that of Japan as a whole.

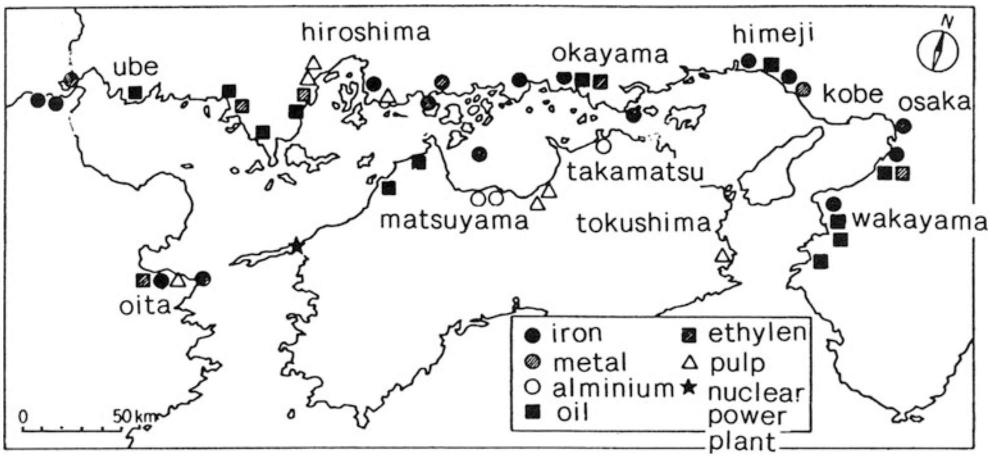


Fig. 3.7 Industrial areas and large cities around the Seto Inland Sea

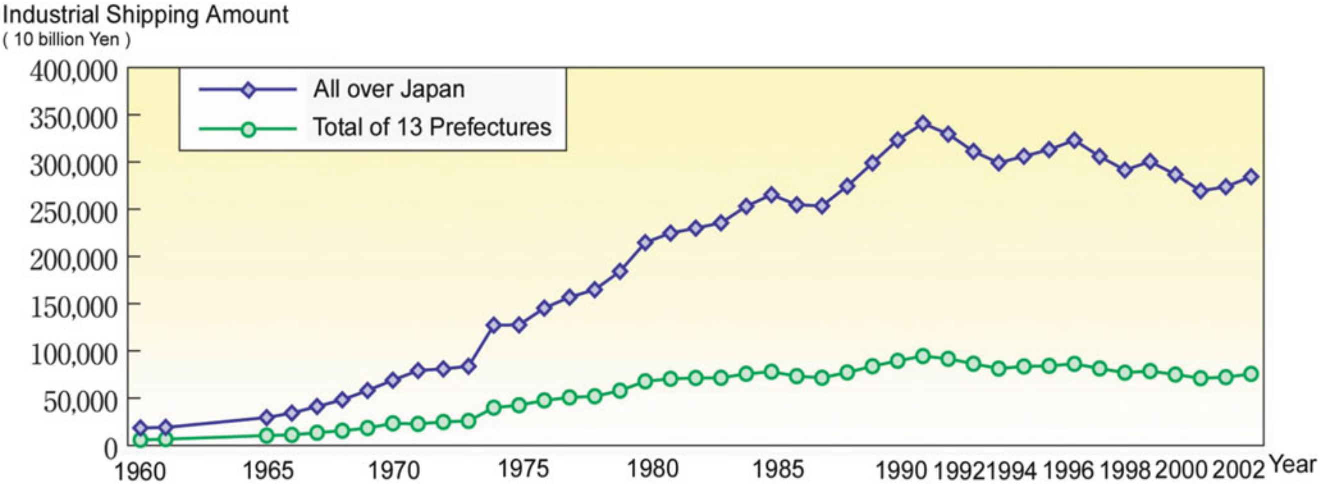


Fig. 3.8 Trends in manufacturing shipments in the prefectures concerned (Source: Ministry of International Trade and Industry)

3.2.3 Coastline

Since ancient times, the coastline of the Seto Inland Sea has been changed by reclamation for agriculture and salt farm land because of its shallow depth. The rapid industrialization that was undertaken from the 1960s required a great deal of reclamation, and, as a result, the natural coastline is only 37 % of the total coastline of the Seto Inland Sea at present (Fig. 3.9), which is less than the value for Japan as a whole (55.2 %).

Man-made beaches have been created to restore lost natural beaches. The state of the coastline along the Seto Inland Sea is shown in Fig. 3.10.

3.2.4 Dams

Many dams were constructed in the watershed area of the Seto Inland Sea and the number constructed was at its largest in 1966–1970, with about 10 per year as shown in Fig. 3.11. A total of about 600 dams are distributed in the watershed area of the Seto Inland Sea as shown in Fig. 3.12.

3.3 Status

3.3.1 Water Quality

The horizontal distributions of salinity, TP (total phosphorus), TN (total nitrogen), and Chl.*a* (chlorophyll *a*) in surface water during the summer of 2003 are shown in Figs. 3.13, 3.14, 3.15, and 3.16.

Low salinity was observed in the inner part of Osaka Bay and Hiroshima Bay, while high TP and TN were observed in the inner part of Osaka Bay, Hiroshima Bay, and Beppu Bay. High Chl.*a* was also observed in the inner part of Osaka Bay, the western part of the Kii Channel, the northern part of Harima-Nada, and Hiroshima Bay where high TP and TN were observed.

3.3.2 Sediment Quality

Generally, sediment quality in the sea is deteriorating, particularly in areas with stagnant water or a small tidal current. The horizontal distributions of mud content, TP, TN, and ORP (oxidation reduction potentials) in sediments from 2001 to 2005 are shown in Figs. 3.17, 3.18, 3.19, and 3.20. High TP and TN were observed in Osaka Bay, Harima-Nada, Hiuchi-Nada, Hiroshima Bay, the southwestern part of Suo-Nada, and Beppu Bay where mud content was high. Naturally, low ORP was observed in these areas.

Fig. 3.9 Natural coast line in the Seto Inland Sea (Provided by Chugoku Press)

The horizontal distributions of individuals, number of species, and the diversity index of macro-benthos in sediments are shown in Figs. 3.21, 3.22, and 3.23. High numbers of individuals and of macro-benthos species were observed at Bisan-Seto, in the western part of Bingo-Nada and Aki-Nada where TP and TN were low. Low biodiversity was observed in Osaka Bay, Harima-Nada, Hiuchi-Nada, Hiroshima Bay, the southwestern part of Suo-Nada, and Beppu Bay where TP and TN were high.

Observations of bottom sediment throughout the Seto Inland Sea have been conducted three times by the Ministry of Environment, Japan. The first one was from 1981 to 1987, the second from 1991 to 1996, and the third from 2001 to 2005. In comparing the most recent data with the previous data, no parameters except for ORP changed over the 20-year period in any of the areas. Also, there was no area where sediment quality had further deteriorated, and, in fact,

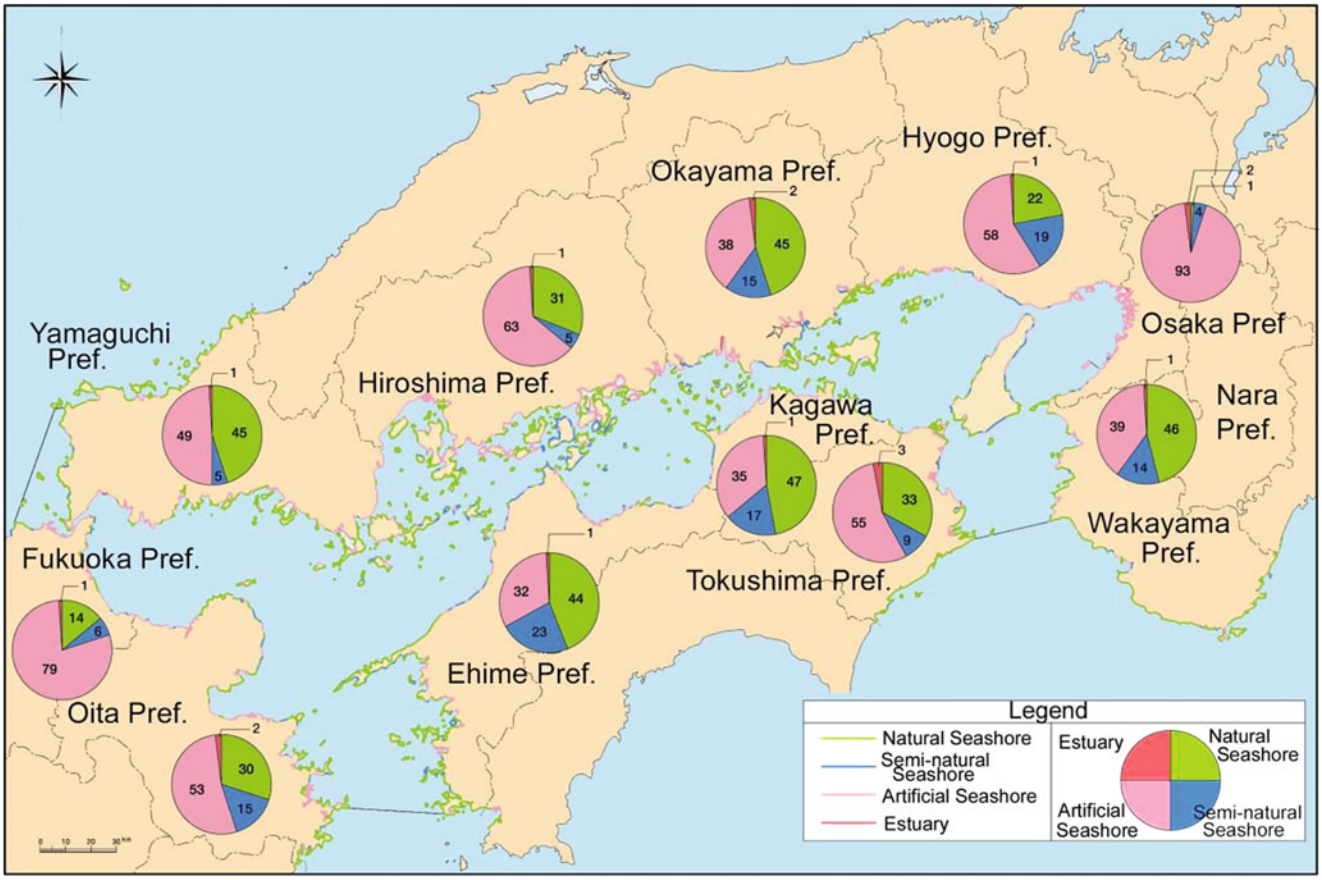


Fig. 3.10 State of the shore line along the Seto Inland Sea (Source: Environment Agency of Japan (fourth survey 1993); Regions of the Seto Inland Sea are based on the Law Concerning Special Measures. For Conservation of The Environment of The Seto Inland Sea)

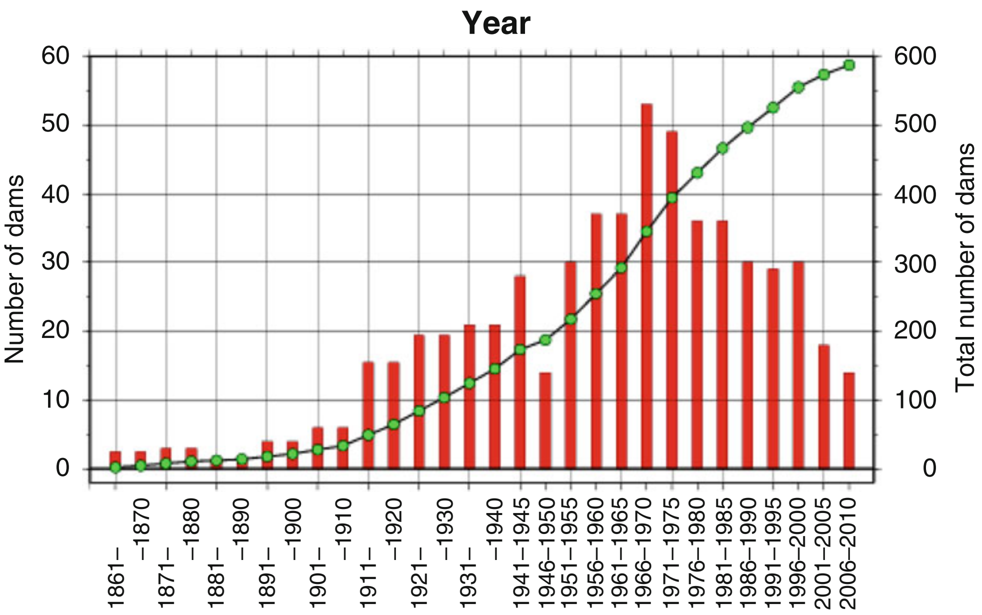


Fig. 3.11 Year-to-year variation in the construction and accumulation number of dams in the watershed area of the Seto Inland Sea

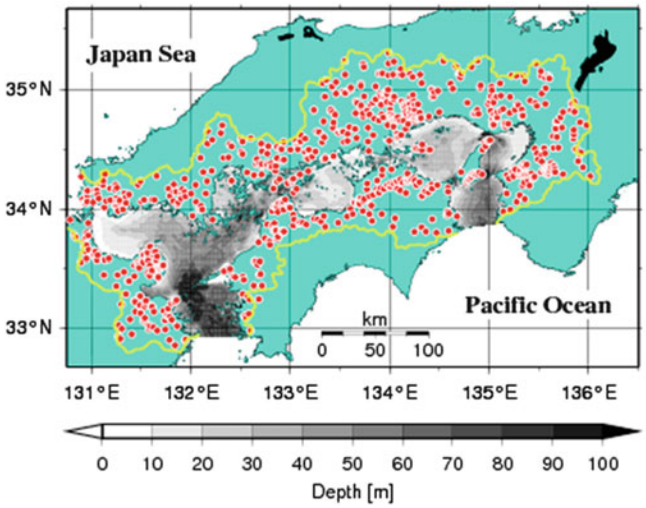


Fig. 3.12 Sites of dams constructed in the watershed area of the Seto Inland Sea

a little improvement in sediment quality was observed in all areas, particularly in Suo-Nada. Based on benthos, three categories for the area can be assigned according to the number of species and the diversity of macro-benthos. The first one is an area where macro-benthos is rich, such as Aki-Nada. The second is an area where macro-benthos is poor, such as in Beppu Bay, Hiroshima Bay, and Osaka Bay. The third is an area where the situation for macro-benthos is between the first two. In comparing the most recent data with the data previously obtained 10 years ago, statistically significant differences in individuals and the number of species of macro-benthos can be observed at Harima-Nada (decrease in individuals); Hiuchi-Nada (decrease in individuals and number of species); Kii Channel (decrease in number of species); Bisan-Seto (increase in number of species); Bungo Channel (increase in number of species); and Aki-Nada (increase in individuals and number of species). In comparing the results of the observation performed by the Fisheries Agency of Japan 20 years ago, it was thought that the number of species and the diversity of macro-benthos had decreased or shown no change in most areas. The main reason of such change is thought to be the effect of continuing hypoxia, as will be shown later.

Based on the correlation between water and sediment environments, it is thought that because of human activities and the small tidal current, it is easy to accumulate pollutants in the sea regions with a high content of sludge in the sediment, although the correlations among the quality of water and sediment and the environment of aquatic animals and plants are not completely understood. With respect to water quality in such sea regions, transparency is generally small during the summer.

Another important factor which controls of sediment quality is the effect of sea-sand mining lasting over a period of more than 50 years that stopped in 2006 in the Seto Inland Sea. Sea-sand mining was carried out over the whole area of the Seto Inland Sea where there was a sandy sea bottom, and this seriously affected the bottom environment due to changes in topography and the seagrass bed due to increases in turbidity. It especially affected the ecology related to sand eels (*Ammodytes personatus*) because the sandy bottom is

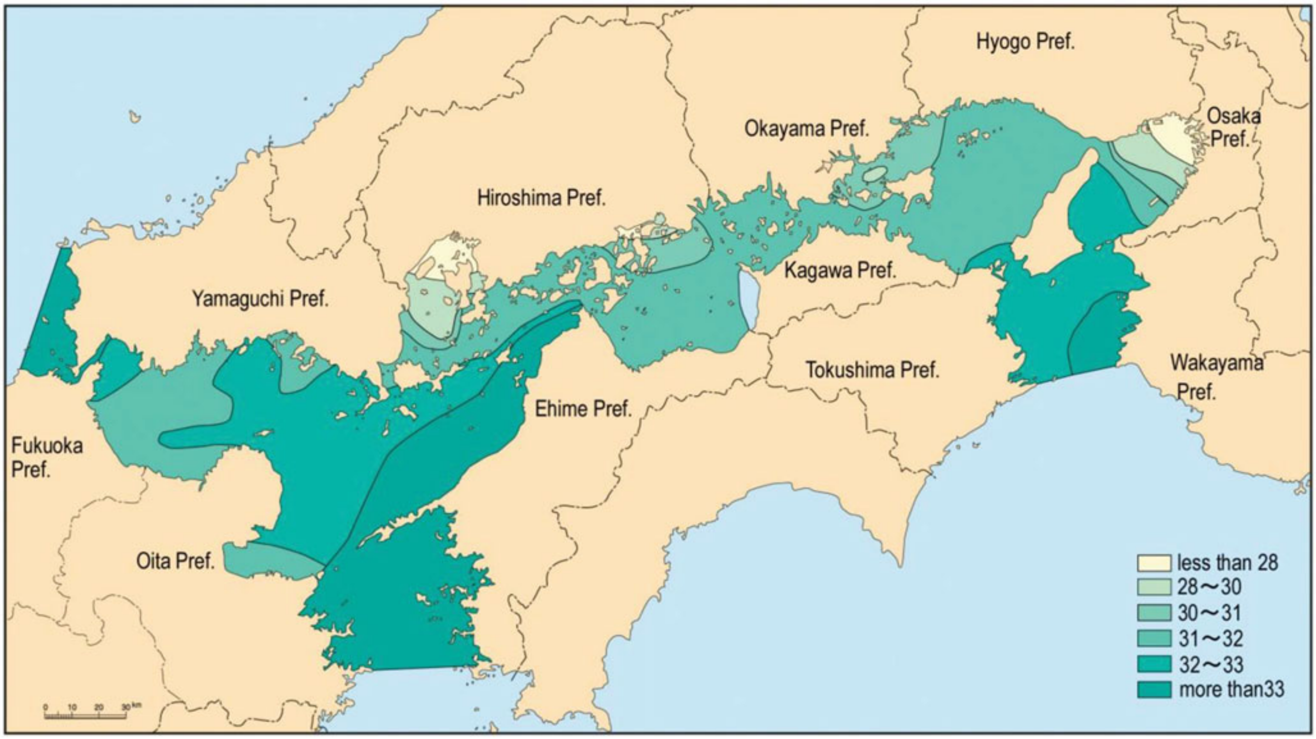


Fig. 3.13 Horizontal distribution of salinity in the surface layer during the summer season, 2003 (Source: Ministry of Environment of Japan 2004)

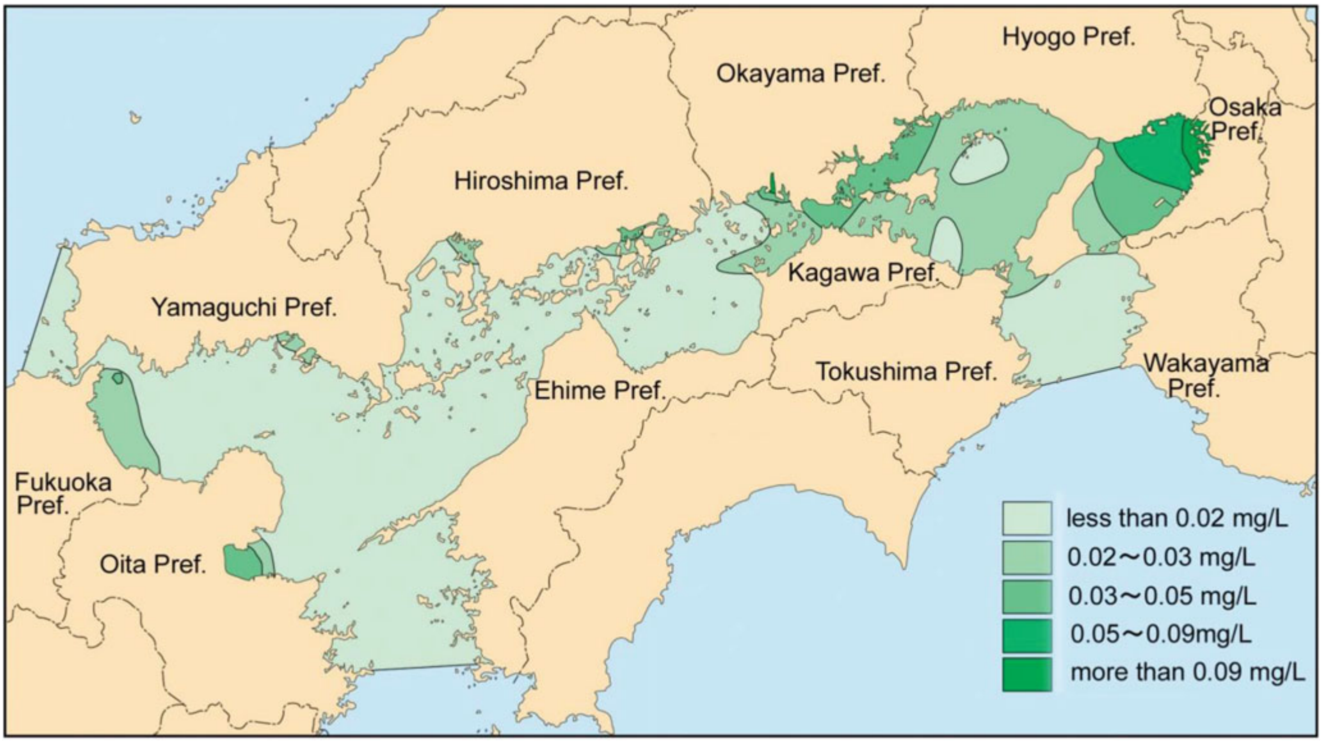


Fig. 3.14 Horizontal distribution of TP in the surface layer during the summer season, 2003 (Source: Ministry of Environment of Japan 2004)

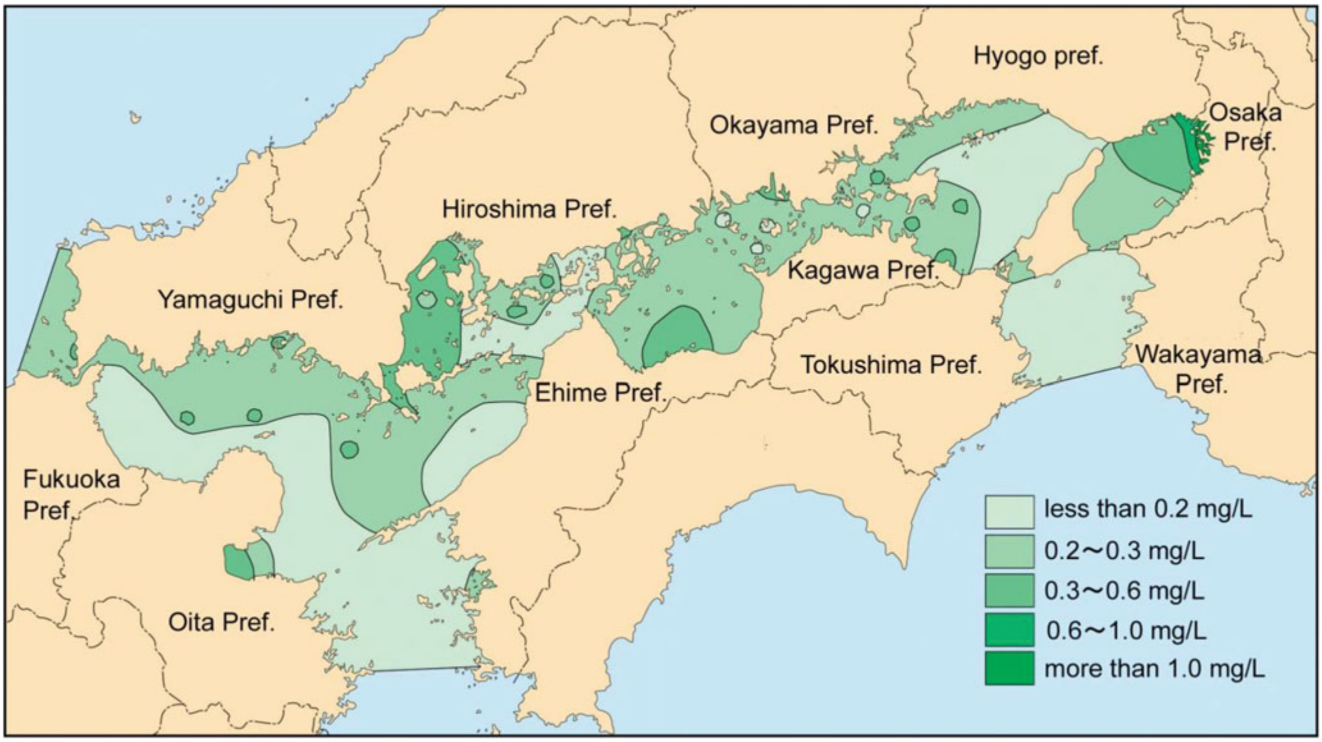


Fig. 3.15 Horizontal distribution of TN in the surface layer during the summer season, 2003 (Source: Ministry of Environment of Japan 2004)

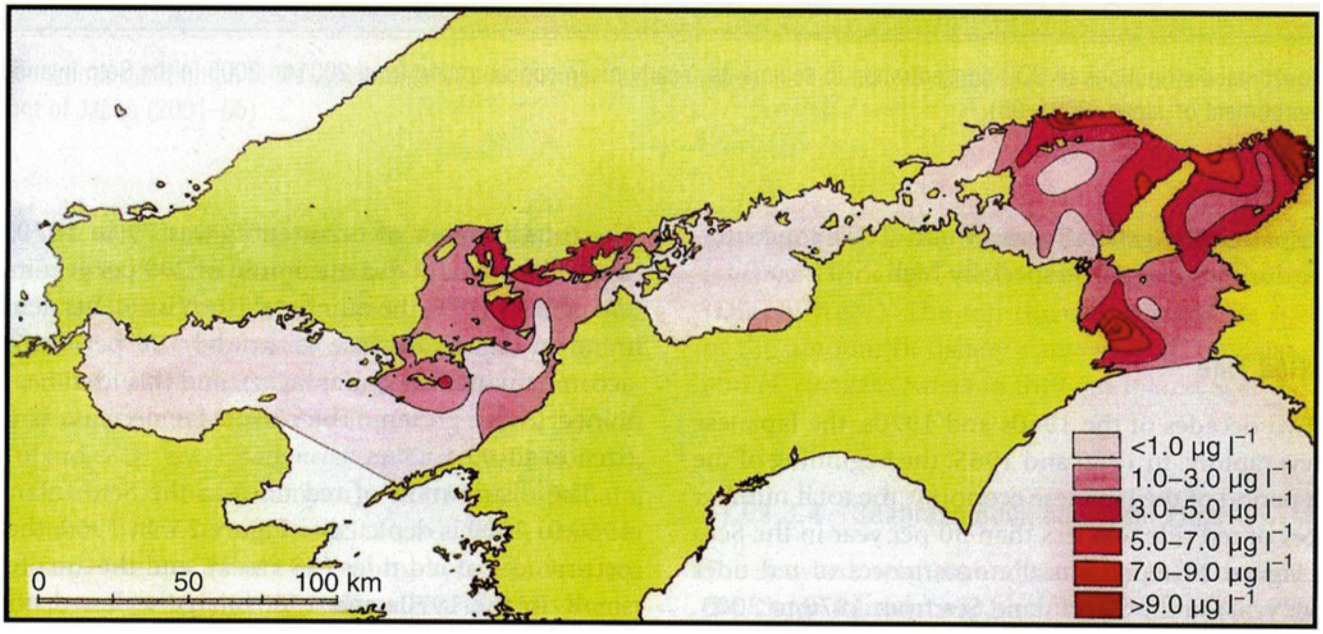


Fig. 3.16 Horizontal distribution of Chl.*a* in the surface layer during the summer season, 2003 (Source: Ministry of Land, Infrastructure and Transport Japan 2004)

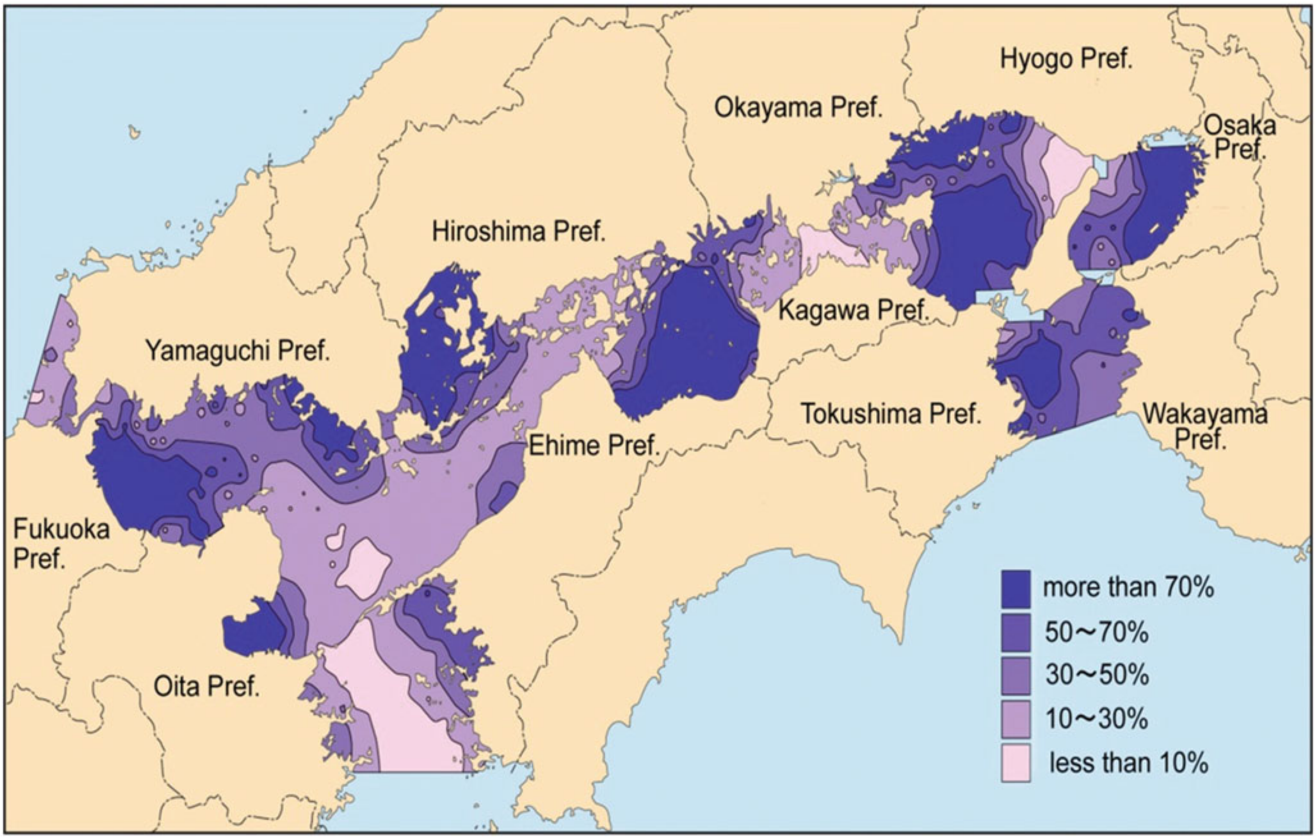


Fig. 3.17 Horizontal distribution of mud content (Source:Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

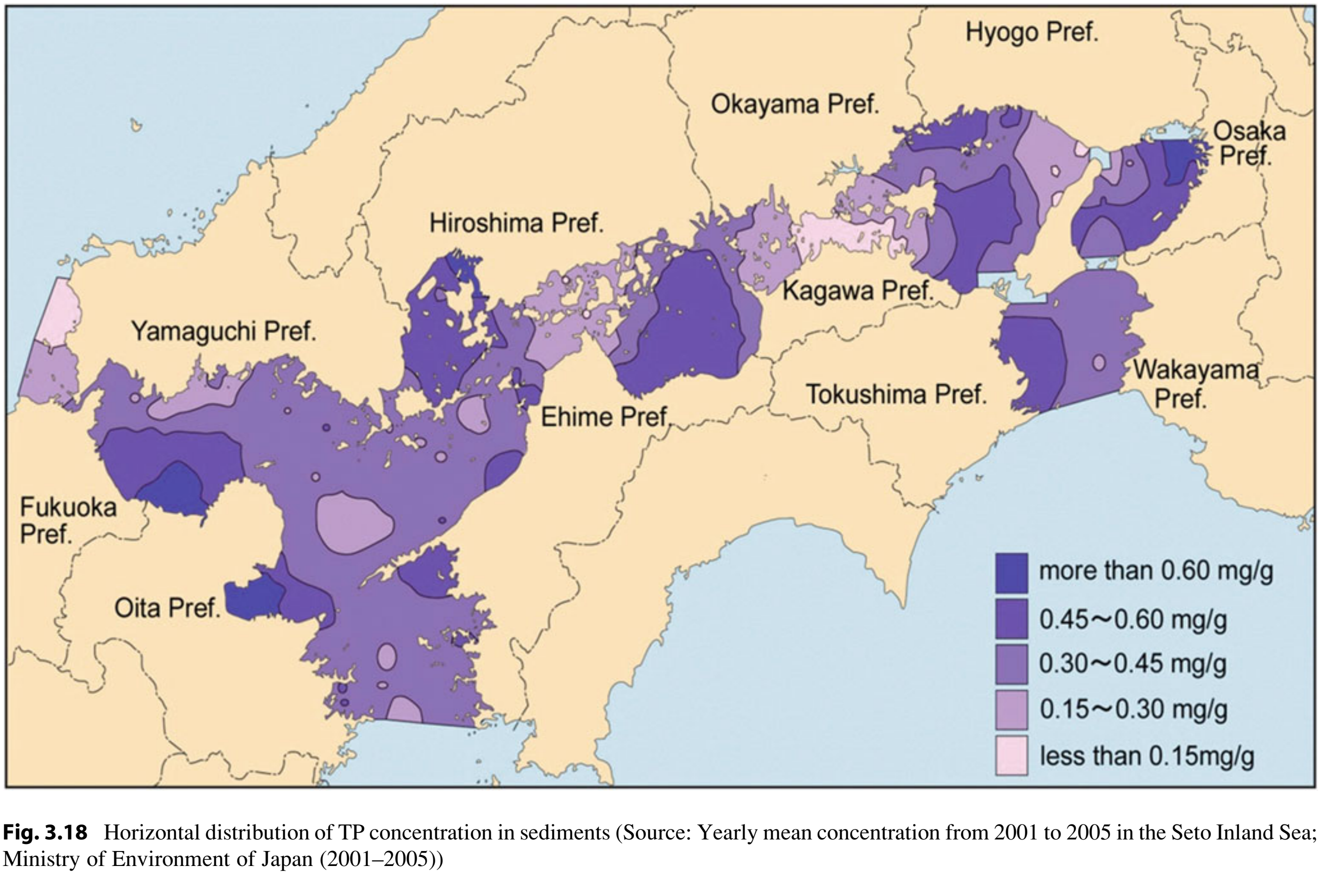


Fig. 3.18 Horizontal distribution of TP concentration in sediments (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

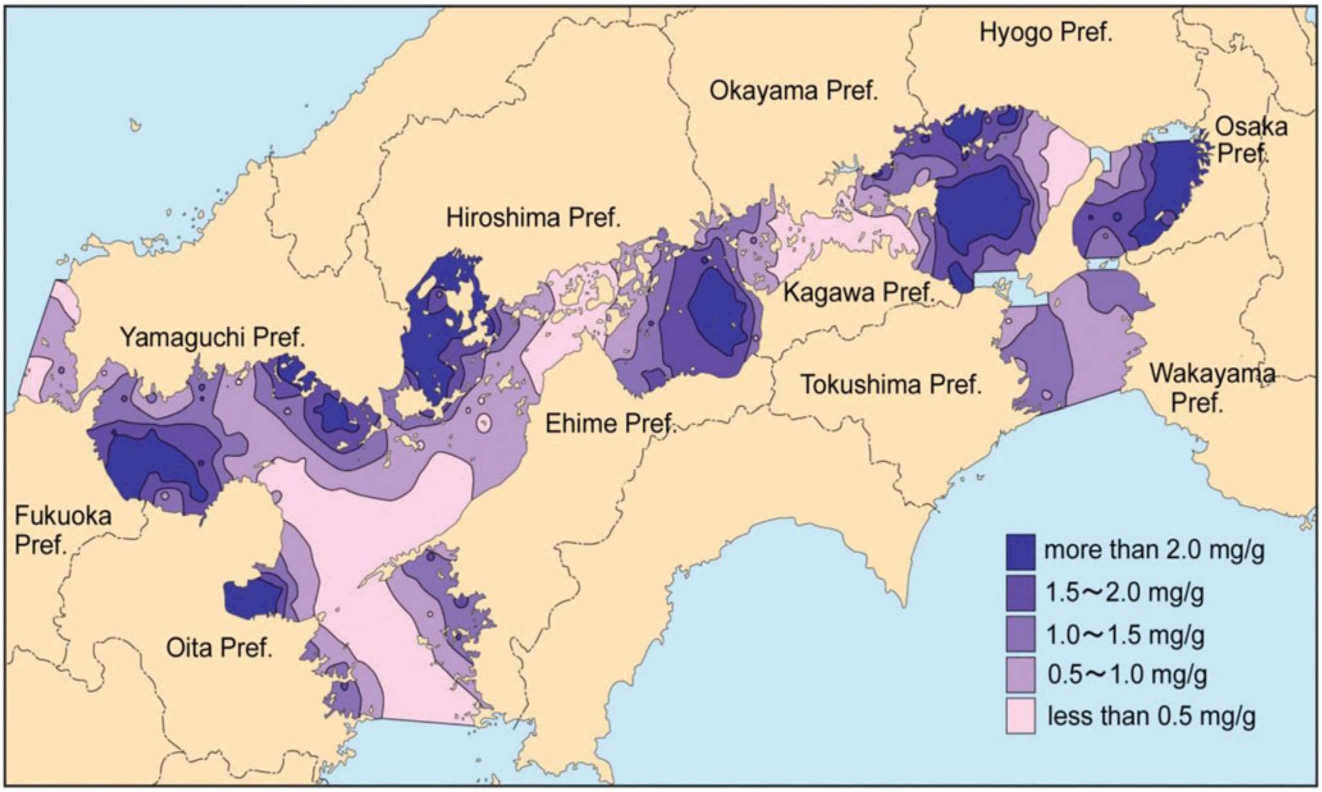


Fig. 3.19 Horizontal distribution of TN concentration in sediments (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

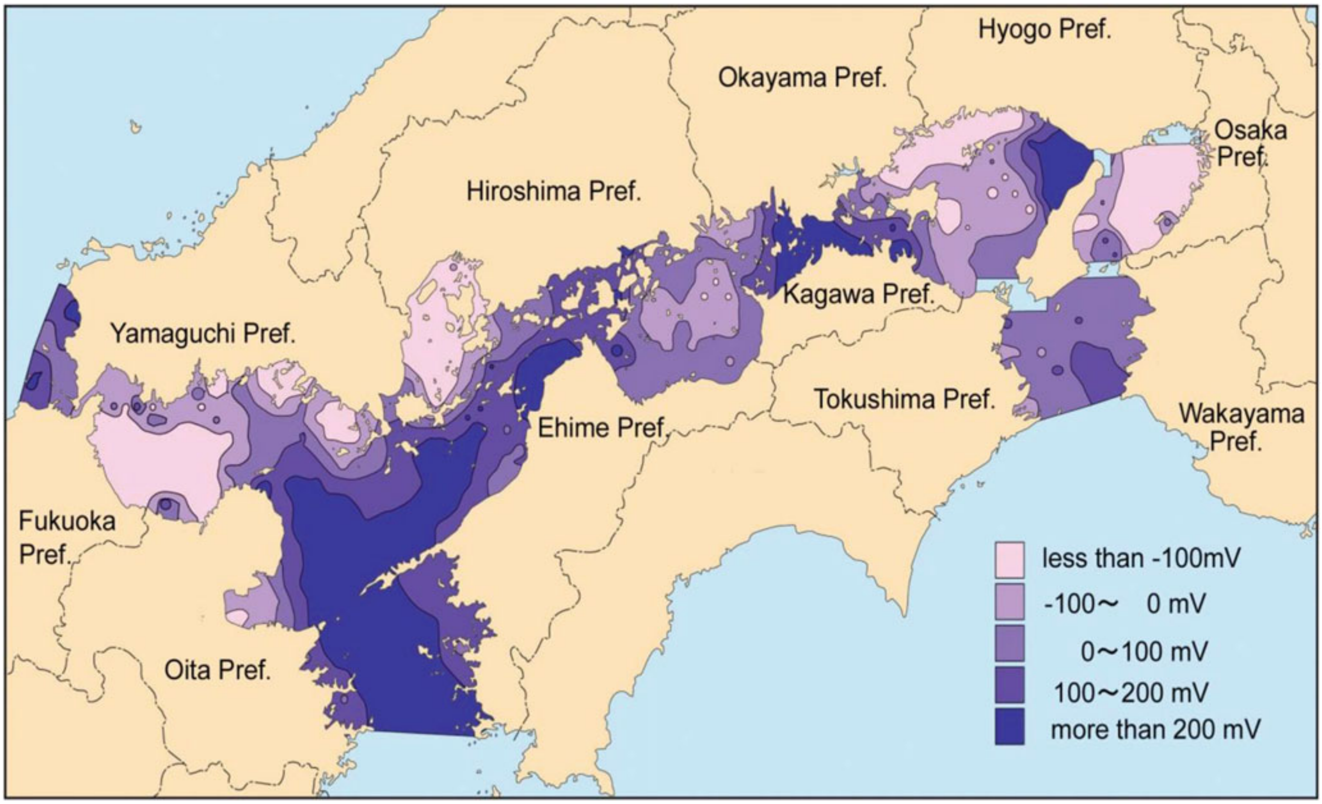


Fig. 3.20 Horizontal distribution of oxidation reduction potential in sediments (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

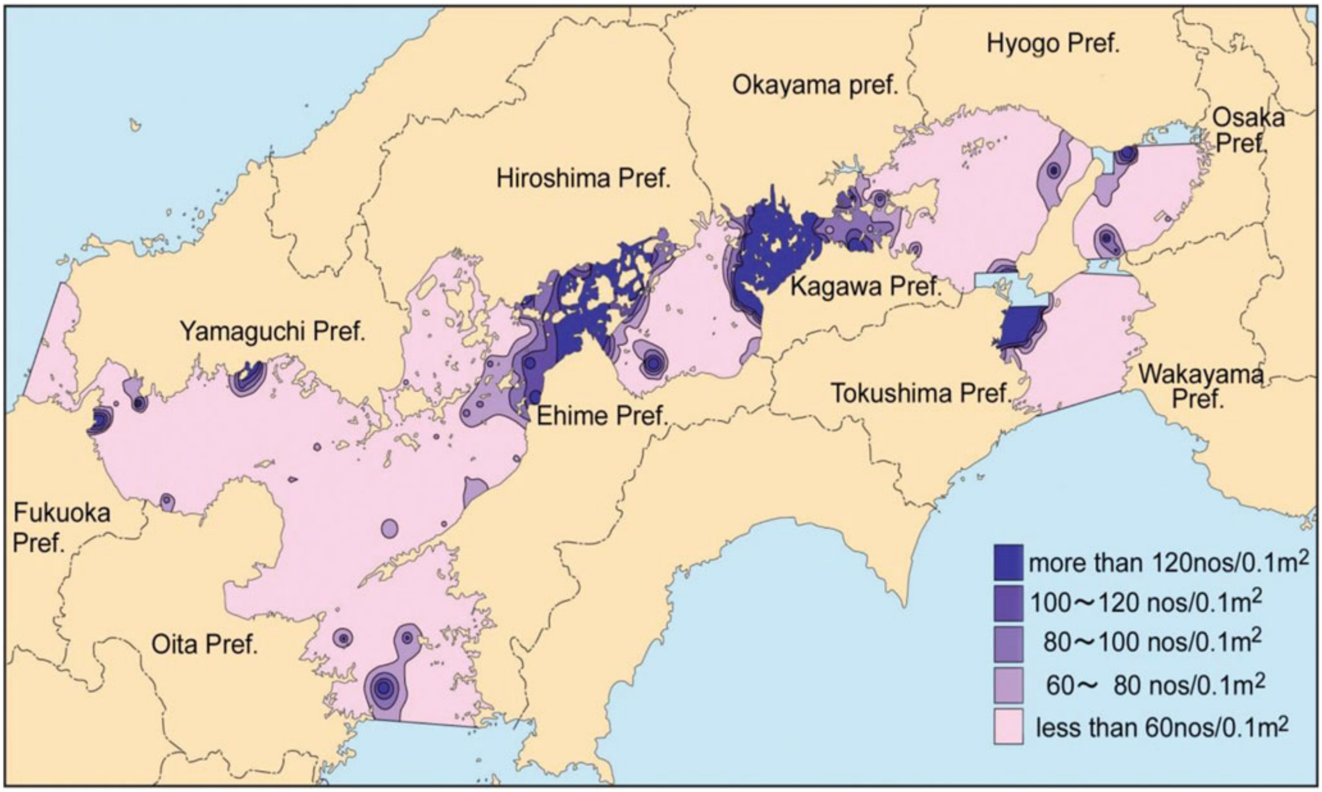


Fig. 3.21 Horizontal distribution of individual macro-benthos in sediments (nos = ind.) (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

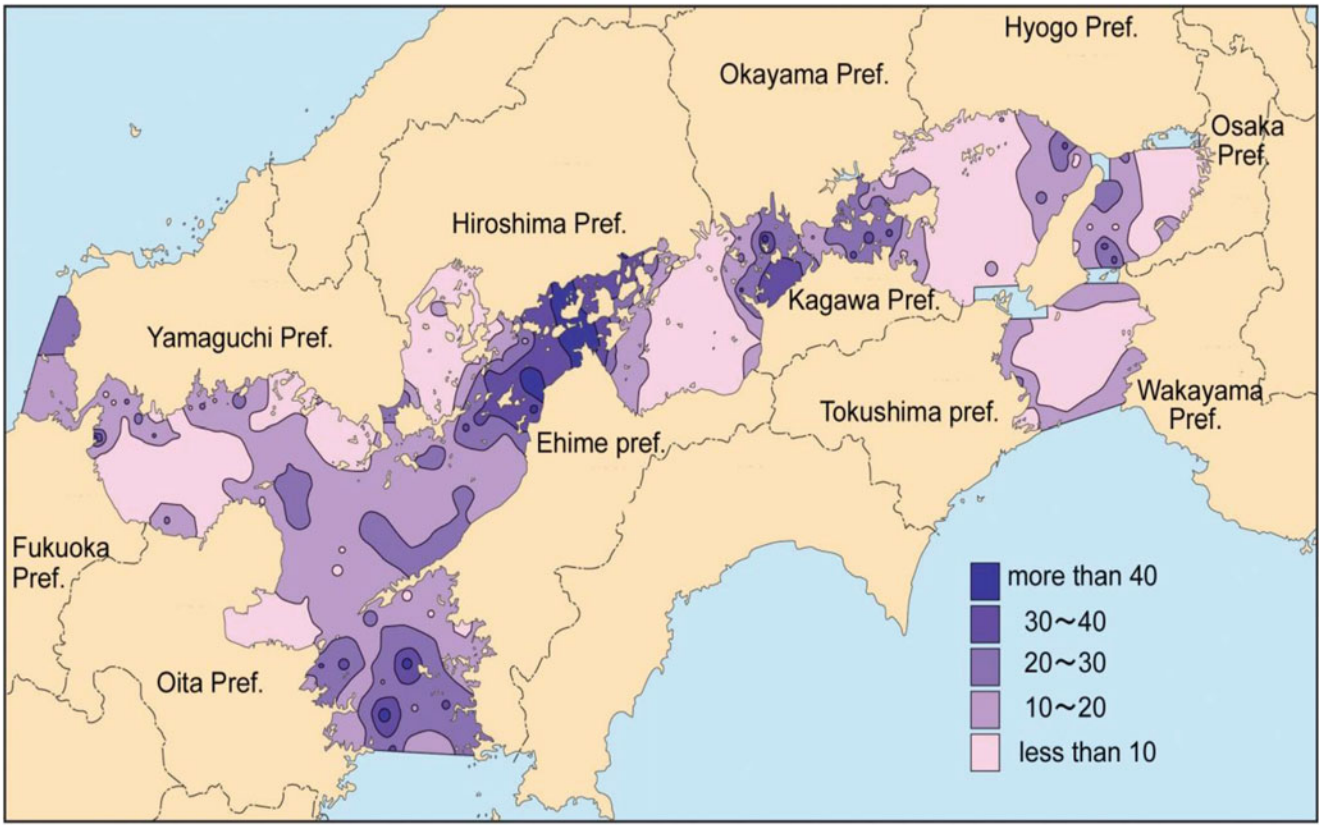


Fig. 3.22 Horizontal distribution of the number of species of macro-benthos in sediments (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

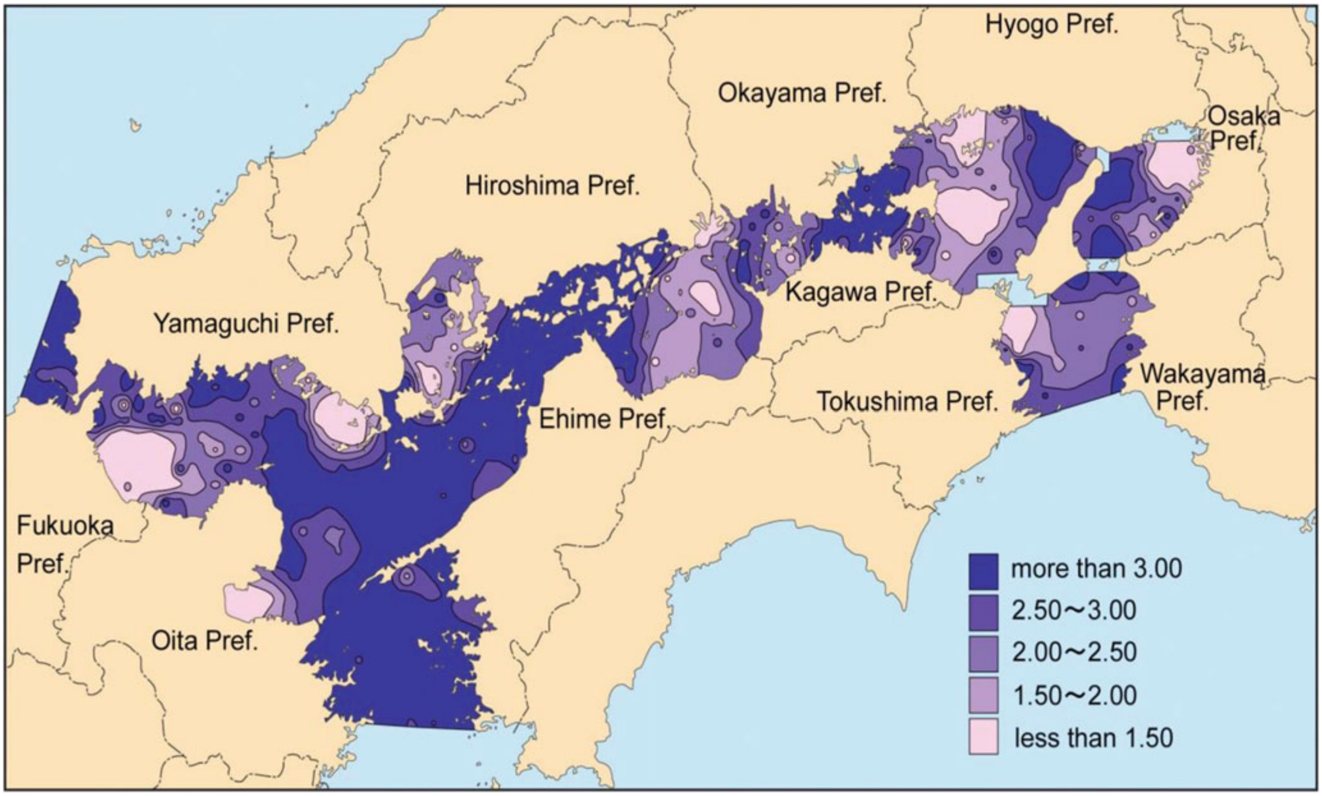


Fig. 3.23 Horizontal distribution of the Shannon-Weaver diversity index of macro-benthos in sediments (Source: Yearly mean concentration from 2001 to 2005 in the Seto Inland Sea; Ministry of Environment of Japan (2001–2005))

where sand eels sleep during the summer months. The effects of sea-sand mining are discussed in Yanagi (2008).

3.3.3 Red Tide

During the two decades of the 1960s and 1970s, the Japanese economy grew rapidly. From 1960 to 1965, the beginning of the period of high growth in the Japanese economy, the total number of occurrences of red tide was less than 50 per year in the Seto Inland Sea (Okaichi 2004). Figure 3.24 represents the number of red tides (incidents per year) from 1967 to 2008. The total number of occurrences was 50 in 1967, showing a marked increment to a maximum of 299 per year in 1976. After the peak in 1976, the number of such incidents demonstrated a trend to clearly decrease to around 100 per year (around 10 accompanying damage of fisheries), and this level has continued to the present time. The reason for this decrease will be discussed in Sect. 3.2.4.

Figure 3.24 is mainly based on the results as seen by local fishermen. Ishii et al. (2014) calculated a Red Tide Index (RTI; 10,000 ha·day) by multiplying the area and the period of red tide occurrences; their results are shown in Fig. 3.25. RTI in the narrow coastal area within 2 km of the coast has a similar magnitude of RTI to the wide offshore area, which suggests that red tides in the coastal area continue for a longer time than in the offshore area. The long-term trend in RTI is similar to that of the number of occurrences shown in Fig. 3.24.

The distribution of red tides in the Seto Inland Sea from 1960 to 2000 is depicted in Fig. 3.26. In the 1960s, there were few occurrences of red tides (18 cases), and the area involved was small. In the 1970s and 1980s, large-scale red tides occurred frequently, especially during the summer. In extreme cases, some red tides covered almost the whole area of the nadas and bays, such as Osaka Bay, Harima-Nada, Hiuchi-Nada, and Suo-Nada. By the 1990s and thereafter, the scale and period of red tides appears to have become smaller and shorter.

Typical microalgae causing noxious red tides in the Seto Inland Sea are *Chattonella antiqua* Hada (Ono), *Heterosigma akashiwo* (Hada) Hada ex Hara et Chihara (Raphidophyceae), *Noctiluca scintillans* (Macartney) Kofoid, *Karenia mikimotoi* (Miyake et Kominami ex Oda) Hansen et Moestrup, *Heterocapsa circularisquama* Horiguchi, and *Cochlodinium polykrikoides* Margalef (Dinophyceae). The top three most noxious species in the Seto Inland Sea in order of the amount of fishery damage are *C. antiqua*, *K. mikimotoi*, and *H. circularisquama* in the Seto Inland Sea.

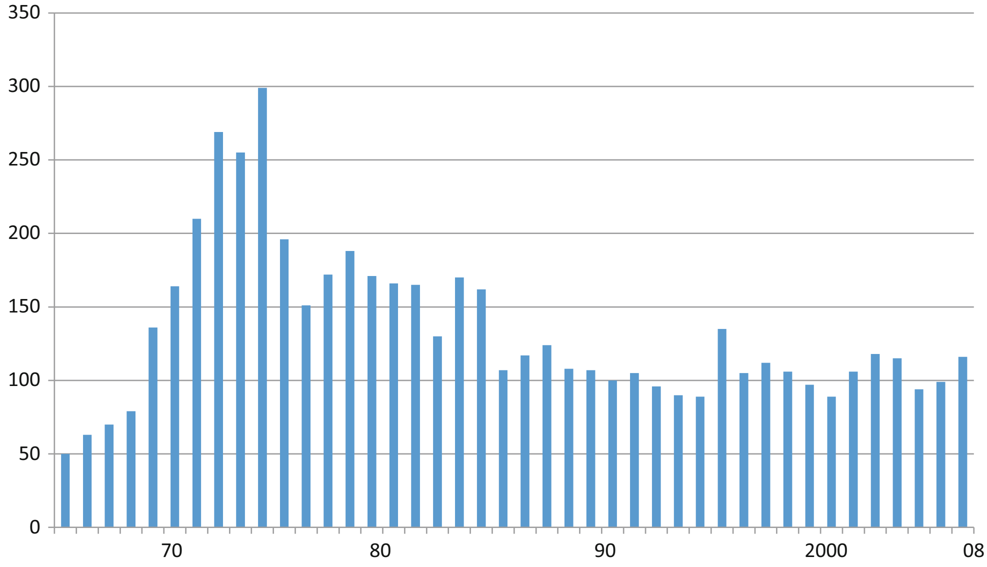


Fig. 3.24 Occurrence of red tides in the Seto Inland Sea from 1973 to 2010

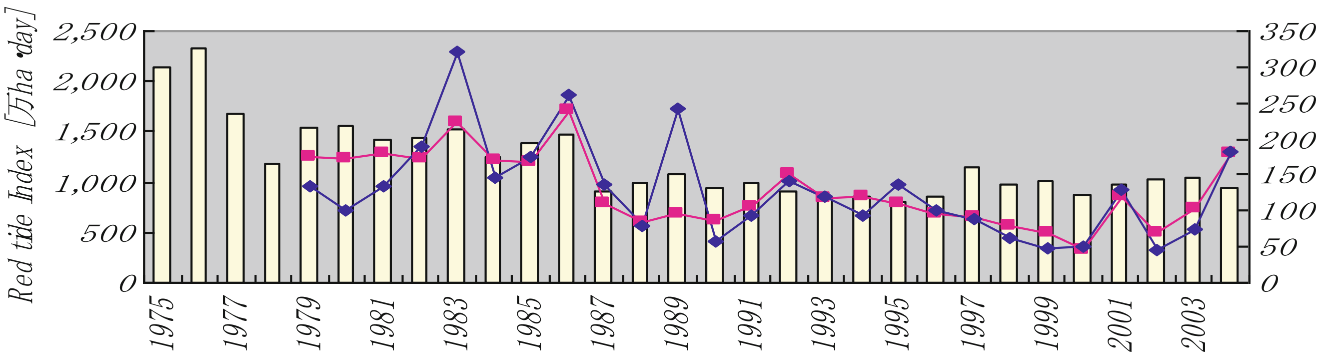


Fig. 3.25 Year-to-year variation in the Red Tide Index in the Seto Inland Sea. Square shows the result in the coastal area, diamonds the offshore area, and bars denote the number of occurrences per year (Ishii et al. 2014)

3.3.4 Hypoxia

Horizontal distributions in DO (dissolved oxygen) concentration above the sea bed in July 1981 and 2000 are shown in Figs. 3.27 and 3.28. Hypoxia (DO is lower than 3.6 mg/l) appeared in the eastern part of Osaka Bay, the central part of Harima-Nada, the eastern part of Hiuchi-Nada, the northern part of Hiroshima Bay, and the western part of Suo-Nada, where Chl.a is high (Fig. 3.16), TP and TN concentrations in sediments are high (Figs. 3.18 and 3.19), and the diversity index of macro-benthos is low (Fig. 3.23). Such distribution of hypoxia showed no change from 1981 to 2000.

3.3.5 Seagrass Beds and Tidal Flats

Seaweed and seagrass beds and the tidal flats in the Seto Inland Sea area have decreased. The former are considered to be important as a zone for nursery grounds of shells and fish. The latter plays an important role in the ecosystem and in self-purification. Trends for each total area are shown in Figs. 3.29 and 3.30.

The area of the Zostera (seagrass) zone is 6,381 ha, while the Garamo (Sargasso) zone is 5,511 ha, and the Ulva and Enteromorpha zone is 4,667 ha. As for the area of the tidal flats, the largest one, covering an area of 6,409 ha, is located in the western part of Suo-Nada and the second largest, 1,022 ha, is in Hiuchi-Nada.

Some fishermen in the Seto Inland Sea have rehabilitated the seagrass beds of eelgrass (Zostera) by spraying their seed for more than 30 years and have succeed in recovering about one third of the area compared to the maximum area of seagrass beds 60 years ago (Yanagi 2012).

3.3.6 Fish Catch

The Seto Inland Sea has an extremely high productivity per unit area of fishery product, which may be due to the two following reasons: one is that essential nutrients needed for

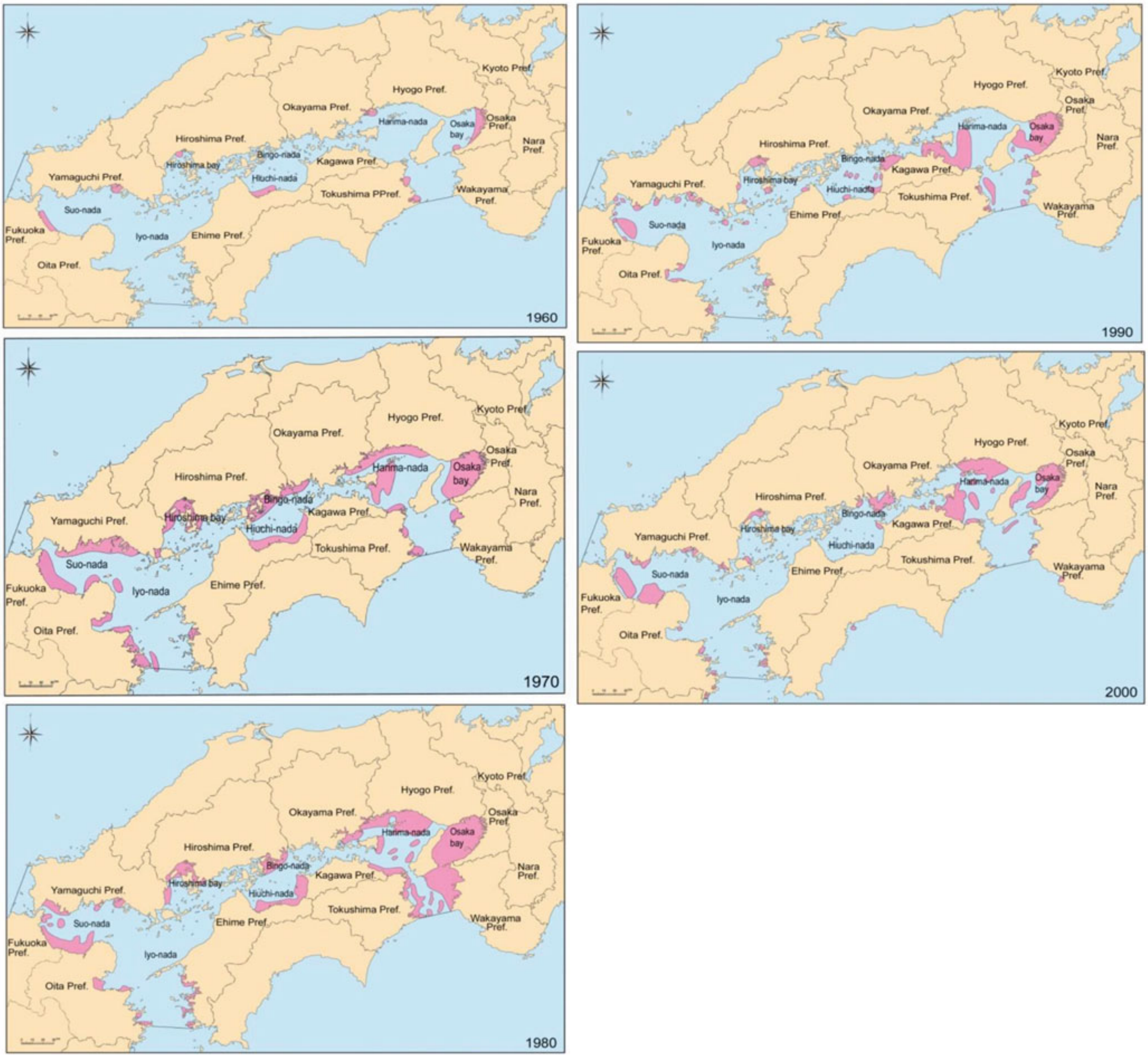


Fig. 3.26 Decadal changes in the distribution of red tide in the Seto Inland Sea

the growth of fish and shells are available thanks to having a sufficient discharge from the many rivers around the sea. The other is the extremely complex and semi-enclosed geography of the sea with its numerous islands, straits, nadas, and the various sizes of its bays (Fig. 3.31, Okaichi and Yanagi 1997). Fish species and the compositions of fisheries and aquaculture productions in 2005 are shown in Figs. 3.32 and 3.33, respectively.

In Fig. 3.32 the total amount of fishery production in the Seto Inland Sea was 198,000 t with the ratio of anchovy (18 %), white bait (10 %), and sand eel (10 %) being rather large. In addition, Fig. 3.32 shows that the total amount of aquaculture product in the Seto Inland Sea was 286,000 t with its large ratio of oysters (47 %) and "nori" (laver; seaweed) (42 %), occupying nearly 90 % of the total.

Oyster and nori culture are very popular in the Seto Inland Sea, which enjoys very calm sea weather as shown in Fig. 3.33.

Figure 3.34 shows the change in fishery production, which increased until around 1985, but it has since been decreasing. The maximum fish catch in the Seto Inland Sea was about 460,000 t/year in 1985. The reasons for this decrease in fish catch, other than anchovy, which has a dominant variability with a period of about 50–70 years on a global scale, are discussed in Sects. 3.3.4 and 3.3.5. On the other hand, average TP and TN concentrations in the Seto

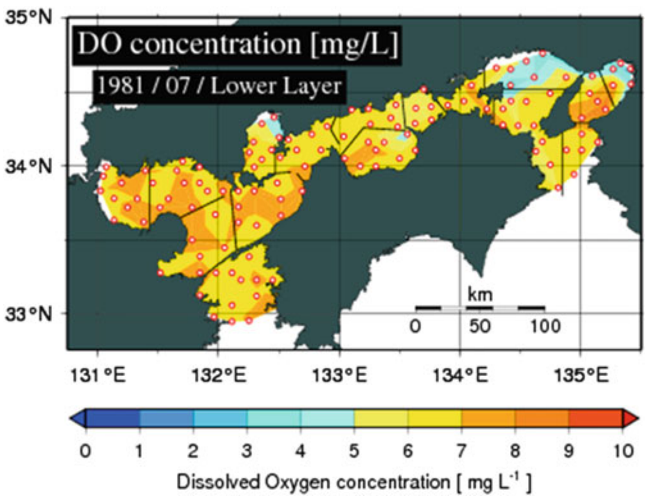


Fig. 3.27 DO concentration above the sea bed in July 1981. *Red circles* indicate the observation station

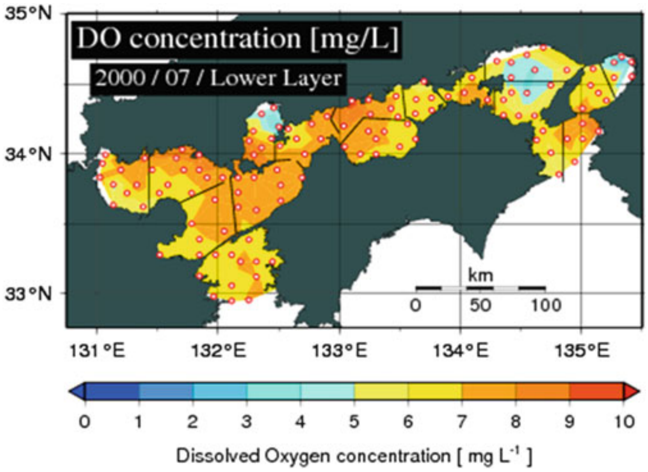


Fig. 3.28 DO concentration above the sea bed in July 2000. *Red circles* indicate the observation station

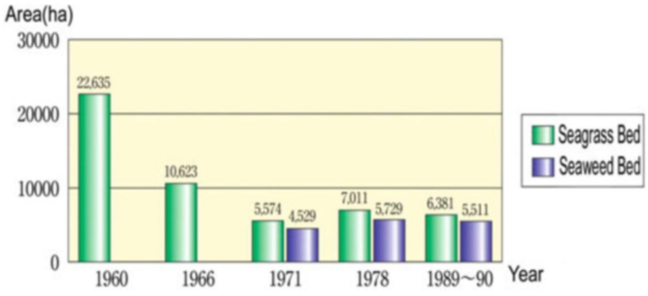


Fig. 3.29 Trends in areas of seaweed and seagrass beds in the Seto Inland Sea (Data from Setouchi-Net)

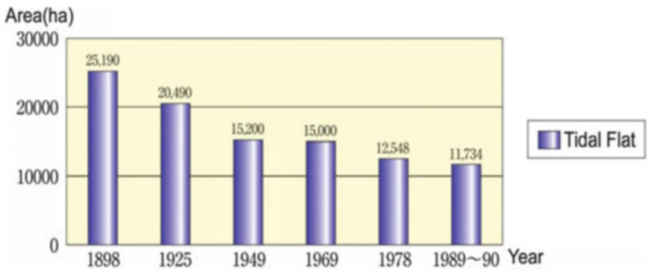


Fig. 3.30 Trends in areas of tidal flats in the Seto Inland Sea (Data from Setouchi-Net) (Source: The Association for the Environmental Conservation of the Seto inland Sea)

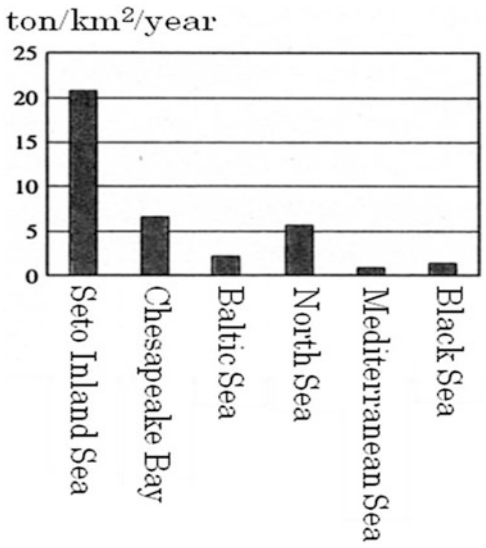


Fig. 3.31 Fish catch per unit area per year in selected semi-enclosed seas in the world. Value for the Seto Inland Sea based on 1985 (Okaichi and Yanagi 1997)

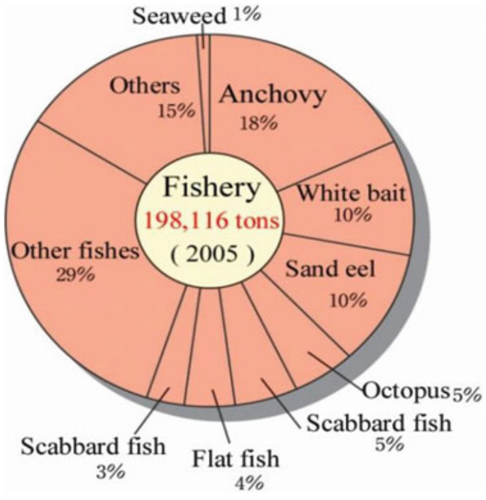


Fig. 3.32 Fish species and composition of fishery production (Source: Ministry of Agriculture, Forestry and Fisheries)

Inland Sea did not change and kept nearly the same value from 1980 to 2005. It is therefore believed that the decrease in fish catch does not have a direct relation to concentrations of TP and TN in the Seto Inland Sea. However, averaged TP and TN concentrations began to decrease from 2007 and may relate to oligotrophication which will be discussed in Sect. 3.3.4.

Various kinds of aquaculture projects have been undertaken to compensate for the deterioration in the living environment of fish and shells, which have a positive effect on the marine production industry in the Seto Inland Sea.

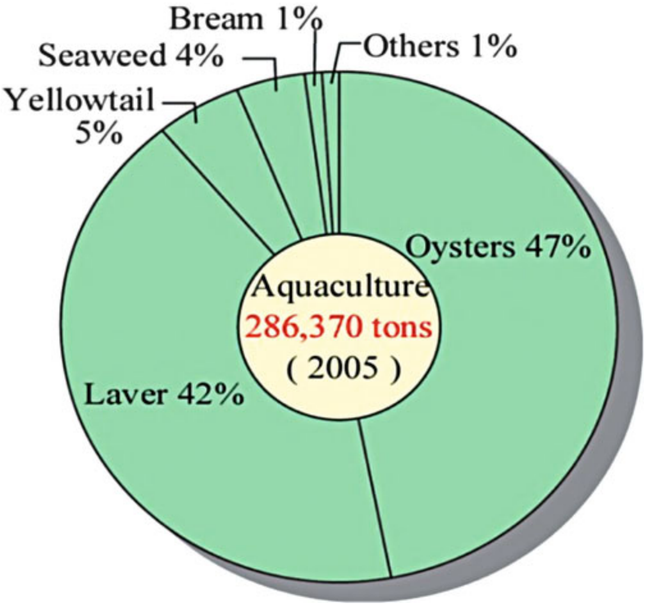


Fig. 3.33 Fish species and composition of aquaculture production (Source: Ministry of Agriculture, Forestry and Fisheries)

3.4 Responses

3.4.1 Special Law

The Tentative Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea (Interim Law) was established on October 2, 1973, based on which the Permanent Law was established on June 13, 1978. The major objective of this Law was to decrease TP and TN loads from land flowing into the Seto Inland Sea in order to stop eutrophication there.

3.4.2 Loads from Land

Trends in TP load are shown in Fig. 3.35. The TP load has tended to decrease slowly since 1974 when the guidance for a reduction in phosphorus load was introduced under the framework of the Special Law. TN load showed a tendency to increase from 1984 as shown in Fig. 3.36. Accordingly, guidance for reduction of TN load was started in 1996 under the framework of the Special Law, and the TN load has decreased since 1994 as shown in Fig. 3.36.

The reduction in TP and TN loads has resulted in the decrease in the occurrence of red tides in the Seto Inland Sea as shown in Fig. 3.24, but it has not resulted in improvement

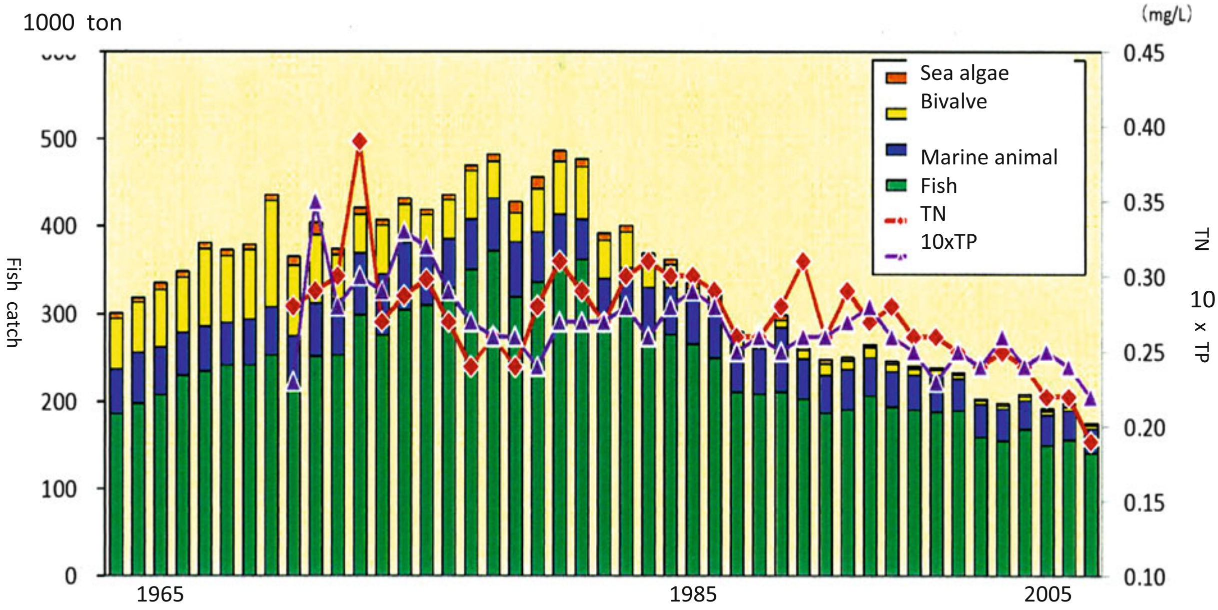


Fig. 3.34 Trends in fishery production and averaged TP and TN concentrations in the Seto Inland Sea (Source: Ministry of Environment)

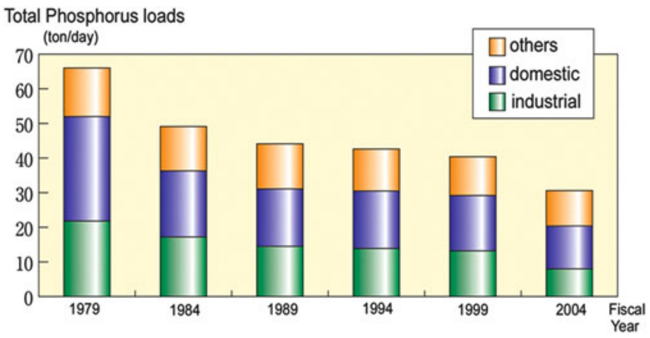


Fig. 3.35 Changes in the total amount of phosphorus load in the Seto Inland Sea (Data from Setouchi-Net) (Source: Ministry of Environment of Japan)

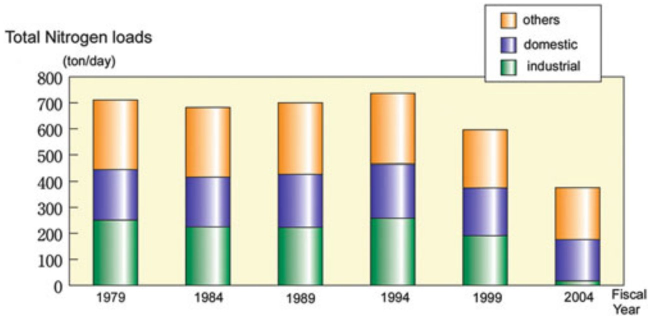


Fig. 3.36 Changes in the total amount of nitrogen load in the Seto Inland Sea (Data from Setouchi-Net) (Source: Ministry of Environmental of Japan)

in water quality (TP and TN concentrations) other than in Osaka Bay.

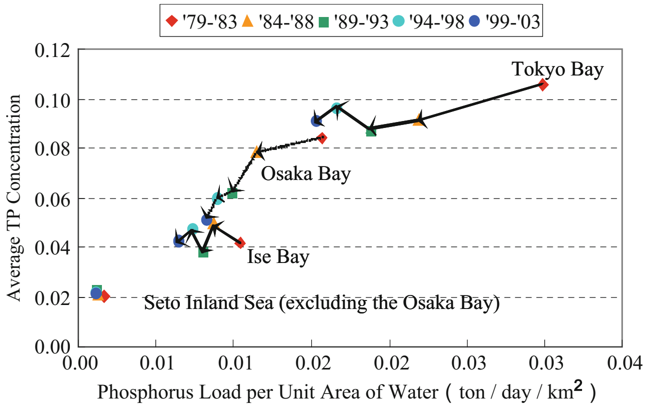


Fig. 3.37 Relationship between TP load and average TP concentration in surface sea water (Source: Ministry of Environment of Japan (2005))

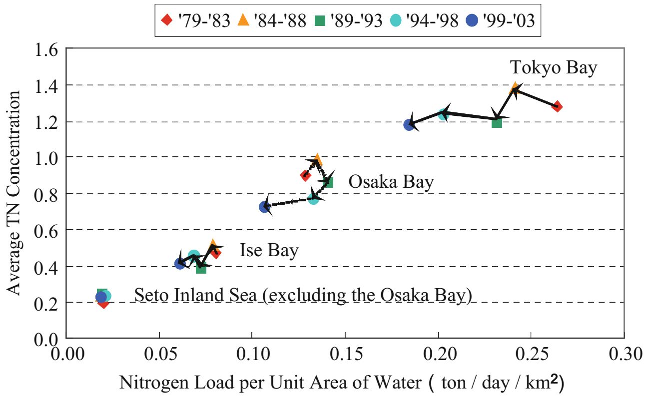


Fig. 3.38 Relationship between TN load and average TN concentration in surface sea water (Source: Ministry of Environment of Japan (2005))

3.4.3 Response in Water Quality and Contribution of Load from Ocean

The relationship between TP and TN loads and TP and TN concentrations in the surface water of the four largest enclosed coastal seas in Japan – Tokyo Bay, Ise Bay, Osaka Bay, and the Seto Inland Sea – is shown in Figs. 3.37 and 3.38. Correlating with the decrease in TP and TN loads, a generally proportional decrease in TP and TN concentrations was observed in Tokyo and Osaka Bays, although the levels of load and concentration differ area-specifically. It should be noted that the nutrient level of Osaka Bay in the Seto Inland Sea is very high compared with that in other areas of the Seto Inland Sea. Estimated TP load in 1979 amounted to 62.91 t/day in the Seto Inland Sea and 41.2 t/day in Tokyo Bay, while TN load was 666 t/day and 364 t/day, respectively. According to the decrease in TP and TN loads, relatively proportional decreases in TP and TN concentrations were also observed in Tokyo and Osaka Bays, but not Ise Bay and the Seto Inland Sea, although the relationships between phosphorus and nitrogen differ slightly. These results suggest that the quality of surface water mainly depends on phosphorus and nitrogen loads coming from the land in Tokyo and Osaka Bays but not in Ise Bay and the Seto Inland Sea.

The reason for different response in water quality to decrease of TP and TN loads in the Seto Inland Sea (excluding Osaka Bay) from that in Tokyo and Osaka Bays is explained by Yanagi and Tanaka (2013), where it is pointed out that the origin of TN and TP is mainly from the Pacific Ocean and the bottom as shown in Fig. 3.39. As shown, about 56–57 % of TP and TN in the Seto Inland Sea originate from the Pacific Ocean, and 33 % of TP and 28 % of TN from the bottom by release. Only 11 % of TP and 15 % of TN originate from the land. Therefore, the effect of decreasing TP and TN loads from the land does not have a large effect on the water quality in the Seto Inland Sea. The ratio of airborne TP and TN to the Seto Inland Sea is less than 10 % (Yanagi 1997).

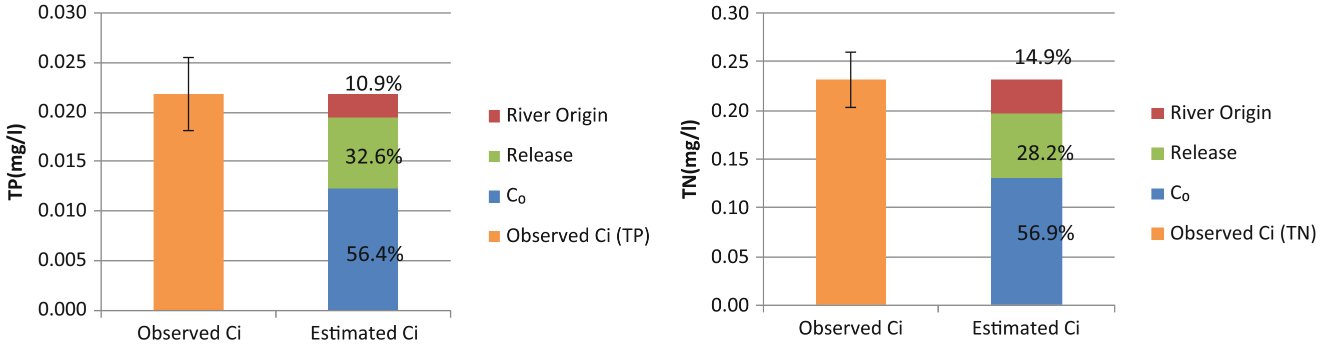


Fig. 3.39 The origin of TP and TN in the Seto Inland Sea (Yanagi and Tanaka 2013)

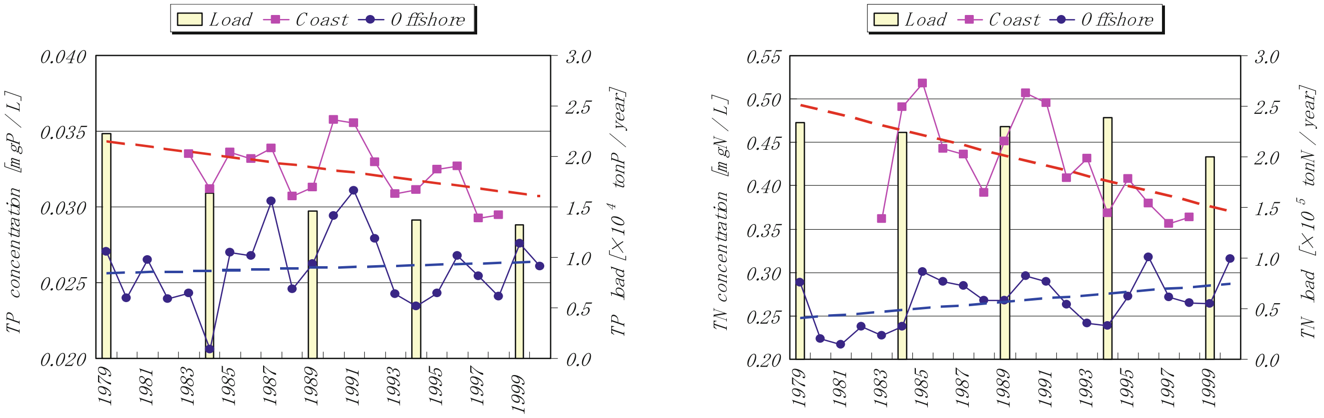


Fig. 3.40 Variation in TP and TN concentrations in the nearshore and offshore areas of the Seto Inland Sea (Ishii and Yanagi 2005)

Year-to-year variations in TP and TN concentrations in the Seto Inland Sea are shown in Fig. 3.34. TP and TN concentrations did not change during these 20 years as shown, except for the last 4 years. Although average TP and TN concentrations in the offshore area of the Seto Inland Sea did not change or increased a little during this time, concentrations in the coastal area within 2 km of the coast decreased as shown in Fig. 3.40 (Ishii and Yanagi 2005).

3.4.4 Reclamation

Heavy industries such as steel, petrochemicals, and shipbuilding have been concentrated in the Seto Inland Sea since the 1950s. In the process, many coastal areas have been reclaimed for industrial sites and ports. The total area of permitted reclamation is very distinct from 1965 to 1973, but decreases drastically from 1974 as shown in Fig. 3.41. It was in this year that the “Tentative Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea” was established. However, reclamation continued in the Seto Inland Sea after 1974 because this Special Law permits the reclamation for public use only, e.g. reclamation for the New Kansai Airport in 1987 or reclamation for waste dumping in 1999.

The land area reclaimed in the Seto Inland Sea since 1898 amounts to 455 km^2, which is equivalent to about 70 % of the area of Awaji Island (the largest island in the Seto Inland Sea). Such large-scale reclamation means that about 20 % of shallow sea with a depth less than 10 m has been reclaimed and has dramatically destroyed seagrass and seaweed beds, tidal flats (as shown in Figs. 3.29 and 3.30), and marine life including benthos.

3.4.5 Oligotrophication

Yamamoto (2003) was the first to point out that the Seto Inland Sea began to undergo oligotrophication based on the decrease of fish catch data from the mid-1980s to the mid-1990s. It does not fully describe the actual situation if we say such a decrease in the fish catch resulted from oligotrophication, since TP and TN concentrations did not decrease in the Seto Inland Sea during the same period as shown in Fig. 3.33.

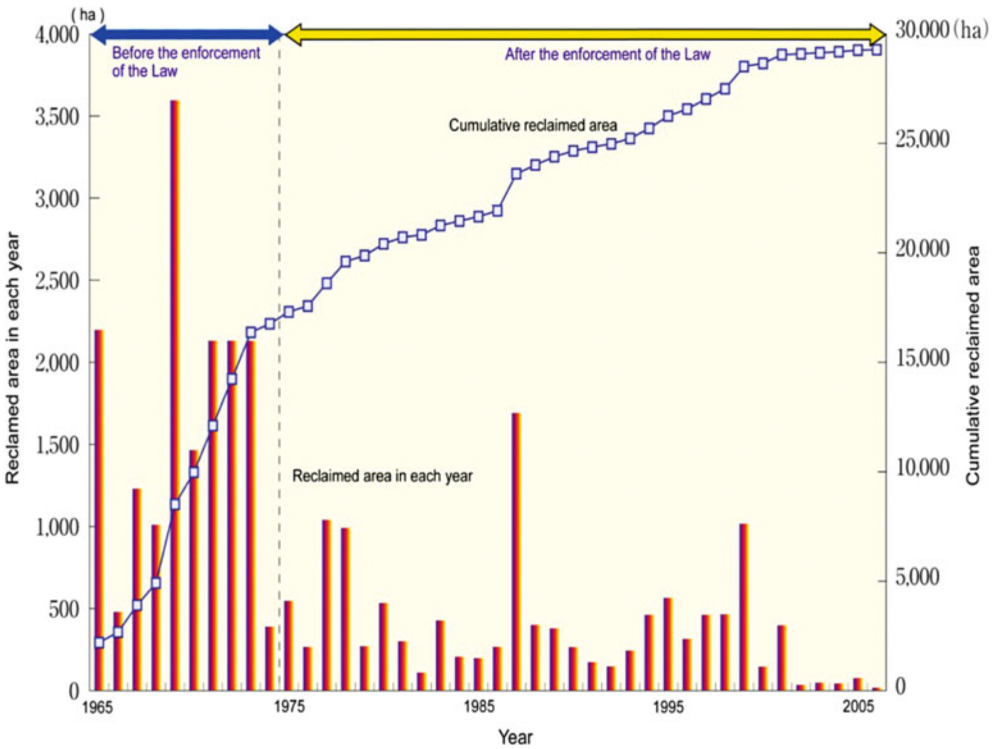


Fig. 3.41 Trends in reclaimed areas in the Seto Inland Sea (Source: Ministry of the Environment of Japan; Data for 1971-1973 show the total from January, 1971 to November 1, 1973; Data after 1973 show the total from November 2 of the previous year to November 1, the following year; A tentative law was enforced on November 2, 1973; Values for 1971–1973 are mean values for the 3 years)

However, the situation has changed in recent years in the Seto Inland Sea. DIN (dissolved inorganic nitrogen) concentration in Harima-Nada and the Bisan Strait has decreased since 1994 (Tada et al. 2010) though TN concentration has remained at nearly the same value. The DIN value in Harima-Nada is only about one tenth of TN (Fig. 3.42). Thus, the limiting nutrient for primary production in Harima-Nada has changed from DIP (dissolved inorganic phosphorus) to DIN from that time as shown in Fig. 3.43. The cell density of the diatom, which is the main species of phytoplankton in Harima-Nada, showed no change but the major species of diatoms has changed from *Skeletonema* spp. to *Chaetoceros* spp. (Fig. 3.44).

Fishing by trawling net began to decrease 2 years after the concentration of DIN decreased in Harima-Nada during the winter as shown in Fig. 3.45 (Tanda and Harada 2011). Nori (sea laver) production in the Bisan Strait has also decreased in recent years as shown in Fig. 3.46 (Tada et al. 2010).

Only a change in DIN without that of TN (Fig. 3.42) suggests that the decomposition of TN into DIN decreases; in other words, material cycling of nitrogen by biochemical processes was active in the past but is not active now. It is suggested that the material cycling of biochemical elements including DIP, DOP (dissolved organic phosphorus), POP (particulate organic phosphorus), DIN, DON (dissolved

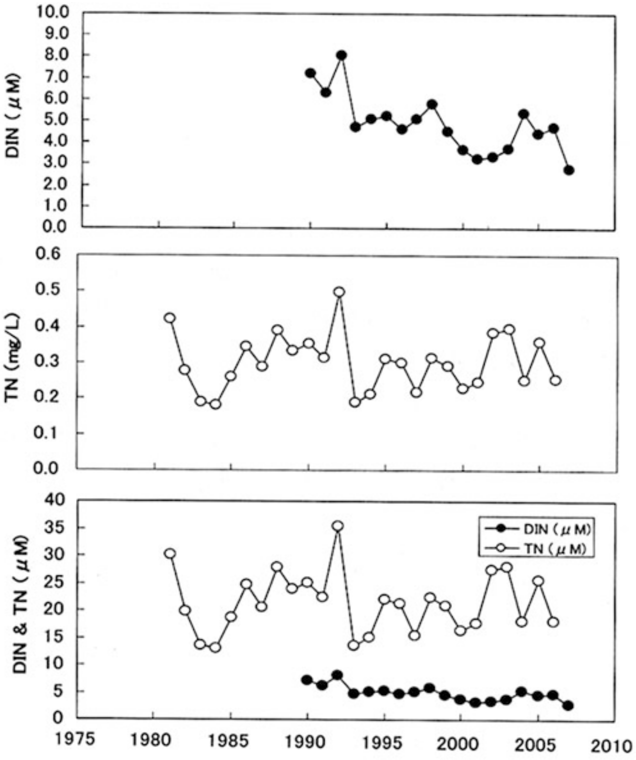


Fig. 3.42 Year-to-year variations in DIN and TN at Harima-Nada in Kagawa Prefecture (Tada et al. 2010)

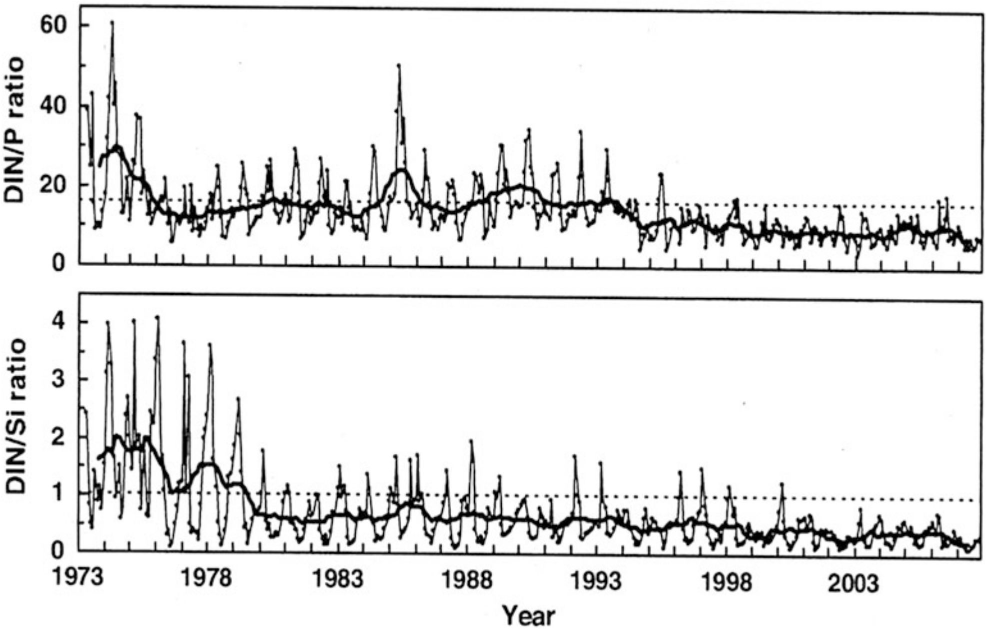


Fig. 3.43 Long-term variations in DIN/DIP and DIN/DSi molar ratios in Harima-Nada over the 35 years from April 1973 to December 2007. Monthly data were averaged for three depths at 19 sampling stations. The smoothed lines were derived from a 13-month moving average. The dashed horizontal lines represent the Redfield ratio (Nishikawa et al. 2010)

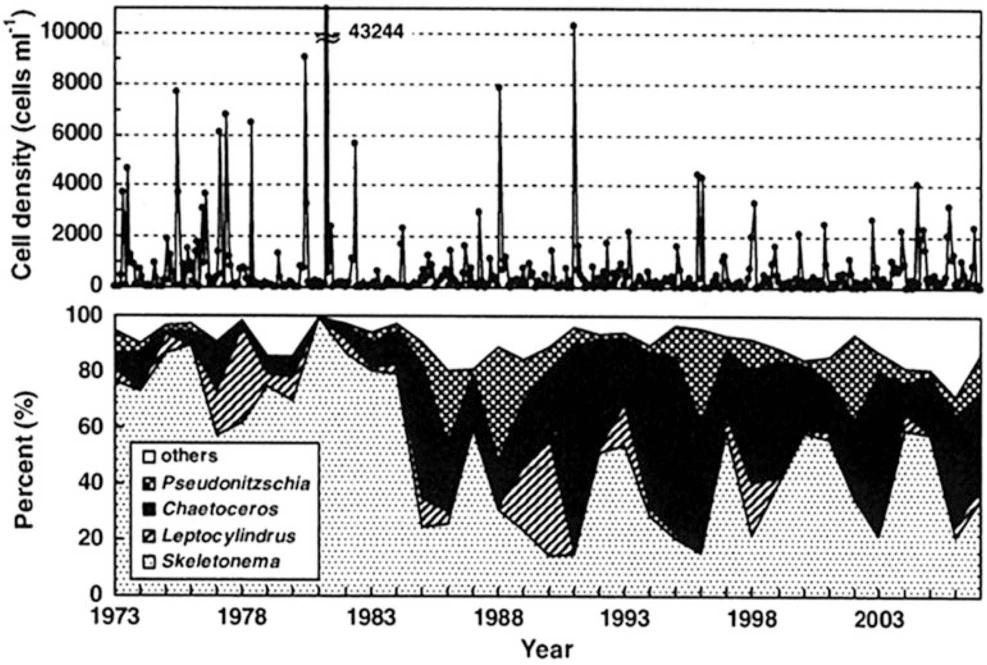


Fig. 3.44 Long-term variations in monthly total cell density and yearly percent species composition of diatoms in the surface layer of Harima-Nada from April 1973 to December 2007. Data on monthly cell densities and yearly composition of species are the average of monthly sampling at 19 stations (Nishikawa et al. 2010)

organic nitrogen), PON (particulate organic nitrogen) has changed in the marine environment, especially the change in related marine ecosystem.

We have to revert to a suitable marine environment based on a healthy marine ecosystem in order to recover healthy and comprehensive material cycling in the Seto Inland Sea.

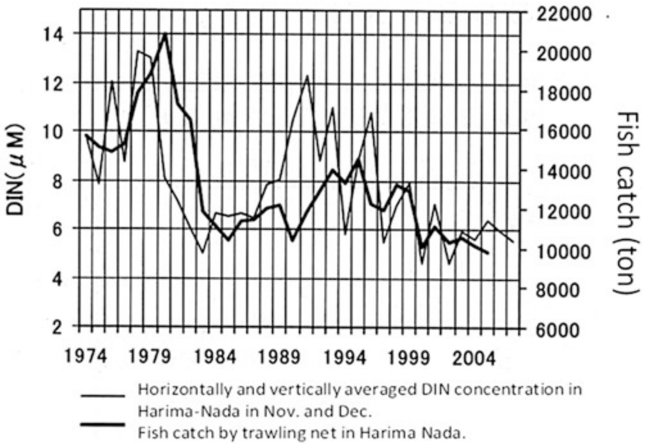


Fig. 3.45 Year-to-year variations in DIN concentration in Harima-Nada and fish catch by trawling net in Harima-Nada (Tanda and Harada 2011)

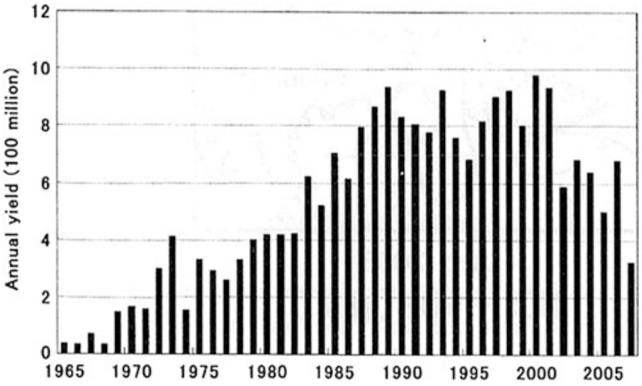


Fig. 3.46 Year-to-year variations in seaweed culture production in Bisan Strait (Tada et al. 2010)

However, the averaged TP and TN concentrations in the Seto Inland Sea began to decrease from 2009 and this is thought to be due to the total TP and TN load control from the land under the framework of the Special Law and also due to the decrease in the bottom release of TP and TN as suggested from Fig. 3.39 as the TP and TN concentrations in the Pacific Ocean have not changed. Therefore, oligotrophication will continue in the future due to the coupling effect of a decrease in TP and TN loads and the decrease in mineralization by biochemical processes.

3.4.6 History of Eutrophication and Oligotrophication

The history of eutrophication and oligotrophication in the Seto Inland Sea is schematically shown in Fig. 3.47. In the 1960s, when the period of rapid economic growth began, nutrient concentrations were low but biodiversity was high, though fish production was not low in the Seto Inland Sea. Due to the increase in nutrient loads from the land during the period of rapid economic growth, nutrient concentrations increased and fish production also increased. The maximum fish catch was attained in 1985. Control of total the nutrient load was begun in 1979 under the framework of the Special Law but the concentrations of TP and TN in the Seto Inland Sea did not change until the 1990s due to the large supply of nutrients from the Pacific Ocean compared to the amount coming from the land. However, biodiversity and the fish production continued to decrease due to hypoxia and the destruction of shallow areas environment, especially the decreasing area of tidal flats and seagrass beds. From the late 1990s, DIN began to decrease mainly due to the change in material cycling of nitrogen related to the change in biochemical processes that resulted from changes in marine ecosystem.

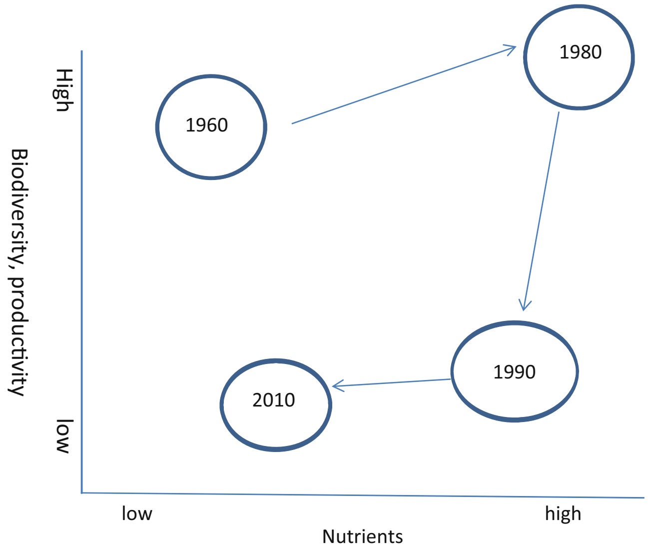


Fig. 3.47 History of eutrophication and oligotrophication in the Seto Inland Sea

Our main objective is to clarify how best to return the biodiversity and production in the Seto Inland Sea from the recent state (2010) to its past state (1960). It is thought that the pathway of changing nutrient concentrations and biodiversity or production during eutrophication is different from that during oligotrophication; in other words, a multi-phase steady state may exist under the same nutrient concentration as shown in Fig. 3.48. Biodiversity and production during eutrophication are thought to be higher than during oligotrophication at the same concentration of nutrients due to the clockwise hysteresis resulting from the effects of hypoxia. We have to clarify such a process quantitatively.

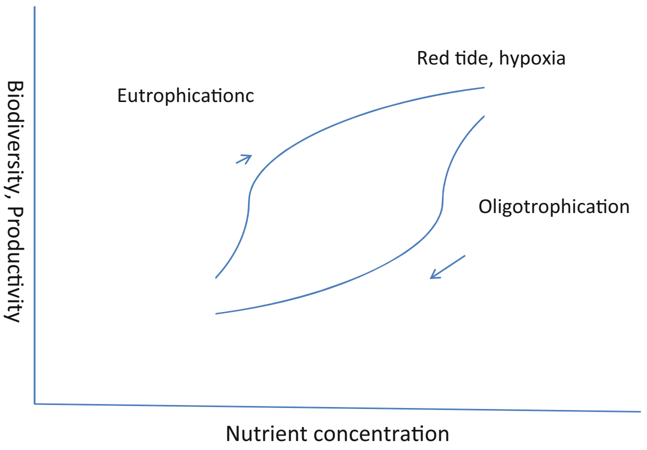


Fig. 3.48 Multiphase quasi-steady state of material cycling and nutrient concentration

3.4.7 Dynamics of Eutrophication and Oligotrophication

The temporal change in biodiversity and productivity is very difficult to study theoretically. Therefore, we look at the temporal change in the phytoplankton community biomass and its relation to the nutrient concentration.

The temporal change in the cell density of phytoplankton (X') is defined by the following Michaelis-Menten formula:

$$\frac{\mathrm{d}X'}{\mathrm{d}t} = G\frac{N}{N+K_S}X' = \alpha X' \tag{3.1}$$

where G, N, and Ks express the maximum growth rate, nutrient concentration, and half-saturation constant, respectively. Therefore, X' is as follows:

$$X' = e^{\alpha t} \tag{3.2}$$

On the other hand, the temporal change in the phytoplankton community biomass (X) is defined by the following sigmoid (logistic) function:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \frac{cX^p}{X^p + h^p} \tag{3.3}$$

where c, p, and h express the constant numbers and $X = \delta X'$. When we consider not only growth but also grazing (beta) and death (γ), Eq. (3.3) is changed to

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \frac{X^p}{X^p + 1} - (\beta X + \gamma) \tag{3.4}$$

Equation (3.4) takes the quasi-steady state ($\mathrm{d}X/\mathrm{d}t = 0$), when the growth rate (first term in the right-hand side) equals the death and grazing rate (second term in the right-hand side). Such a situation is shown in Fig. 3.49 under the condition of $p = 1$, beta $= 0.1$, $\gamma = 0.5$, and $\delta = 1$ with different nutrient concentrations of N.

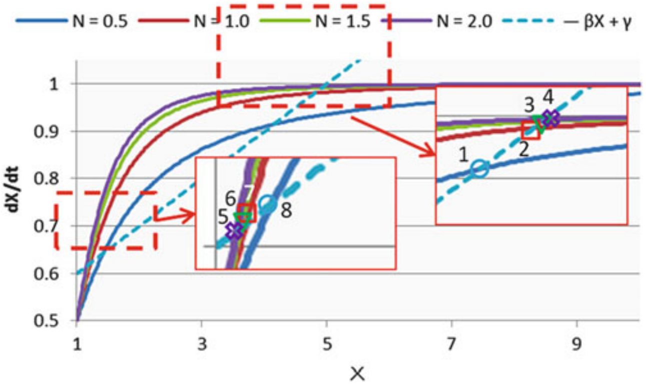


Fig. 3.49 Relation between phytoplankton growth and death and grazing rates when $\mathrm{d}X/\mathrm{d}t = 0$

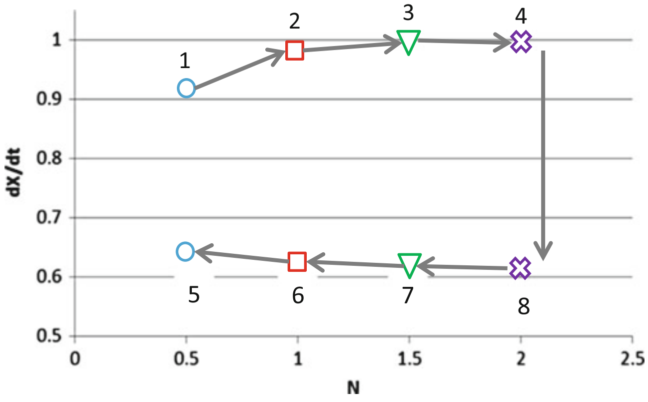


Fig. 3.50 Relationship between nutrient concentration and phytoplankton community biomass

The relation between nutrient concentration and phytoplankton community biomass is shown in Fig. 3.50.

Figure 3.50 corresponds well with Fig. 3.48 qualitatively. The transition from point 4 to point 8 is called the "regime shift" and this regime shift is thought to happen due to the effect of hypoxia. Another regime shift from points 5 or 6 to points 1 or 2 is expected to happen as a result of the disappearance of hypoxia in the Seto Inland Sea.

The reason for the different response in fish catch to the same nutrient concentration is explained by Fig. 3.51. At point A during eutrophication, the dead phytoplankton after a red tide become good bate for the benthos and bottom fish, but at point B, during oligotrophication the dead phytoplankton after a red tide increase the degree of hypoxia due to consumption of oxygen for decomposition. The difference between A and B is based on the accumulation of organic matter in the bottom sediment during eutrophication.

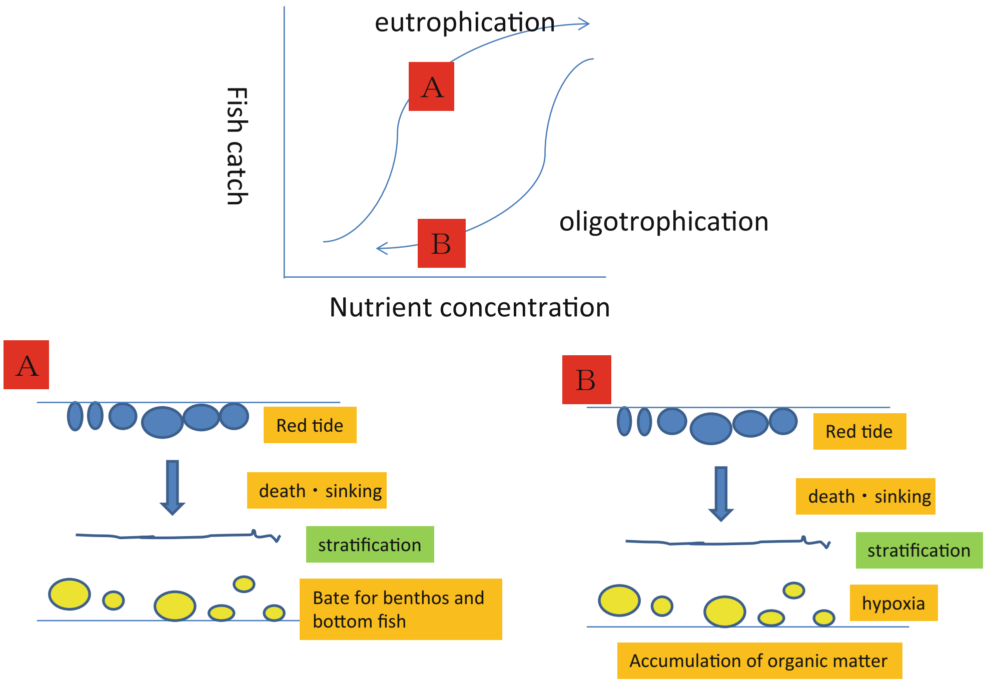


Fig. 3.51 Difference between A (eutrophication period) and B (oligotrophication period) during summer in the Seto Inland Sea

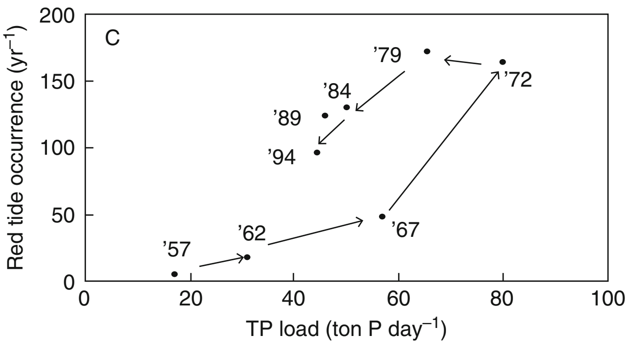


Fig. 3.52 Relationship between TP load variation and the number of red tide occurrences per year (Yamamoto 2003)

A similar hysteresis to Fig. 3.48 is shown in the relationship between the variations in TP load and red tide occurrence as shown in Fig. 3.52 (Yamamoto 2003). In this case the hysteresis is counterclockwise and is also explained by Fig. 3.51, that is, the TP concentration during oligotrophication is higher than during eutrophication due to the DIP release from the bottom sediment at the same TP load.

3.5 Future Tasks

3.5.1 New Environmental Policies

New environmental policies contributing to the recovery of a sound environment were officially introduced to the Seto Inland Sea in 2000 (when the fifth water quality control policy was confirmed). Based on previous environmental conditions, the main target of the policy was changed from water quality control to environmental remediation and restoration of habitat. Led by the new policy for the Seto Inland Sea, a new law for the promotion of nature was enacted in 2002. This new law was applied not only to the Seto Inland Sea but throughout Japan. Collaboration among various groups, such as local and national governments, local residents, NGOs, not-for-profit organizations (NPOs), scientists, and fishermen, is expected to play an important role in promoting individual restoration projects.

Furthermore, in 2006, the sixth water quality control policy was decided on, according to which the total load control policy for TP and TN was maintained only in Osaka Bay but abolished in other bays and nadas of the Seto Inland Sea.

The Basic Act on Ocean Policy was enacted in July 2007, under which the new Headquarters for Ocean Policy takes the responsibility in all governmental activities related to marine affairs and marine environment.

Four possible causes for the decrease in fish stocks in the Seto Inland Sea have been proposed, namely:

1. Changes in the natural environment due to a regime shift (large-scale climatic and oceanographic changes)
2. Overfishing
3. Destruction of spawning and nursery grounds or habitats
4. Long-term changes in the ecosystem due to the effect of human activities

Decreases in sand eel stocks were more directly affected by habitat destruction due to large-scale sea-sand mining for the concrete and construction industries, although sea-sand mining in the Seto Inland Sea was prohibited in 2006.

Among the four possible causes identified above, countermeasures against regime shift and long-term ecosystem change are very difficult or almost impossible to be achieved in a relatively short period of time. Realistic countermeasures can only be taken against overfishing and against destruction of spawning and nursery grounds or habitats. This is where the importance of habitat restoration is key – in particular of tidal flats, seaweed bed, and seagrass bed – and of living resource management in shallow areas.

Shallow coastal waters, seaweed, and seagrass beds are important habitats and reproduction grounds for many marine organisms. Tidal flats provide the most important reproduction area for bivalves. They also play an important role in the decomposition of organic matter, e.g. from DON and PON to DIN. Both of these important habitats have been undergoing long-term decreases in the Seto Inland Sea area. Between 1978 and 1991, 1,500 ha of seaweed and seagrass beds and 800 ha of tidal flats were lost from the Seto Inland Sea as shown in Figs. 3.29 and 3.30, mainly due to reclamation, dredging, or other human activities. As a result, a significant portion of natural coastline has been converted to man-made coastline, consisting of upright concrete structures as shown in Fig. 3.10. These have not provided a good habitat for many organisms living along the seashore, nor have they provided the valuable functions of a natural coastline such as purification of organic pollution and de-nitrification. Such decreases in seaweed and seagrass beds and tidal flats means that the material cycling changed from multi-paths to a simple path as shown in Fig. 3.53.

Of the many enclosed coastal seas of Japan, the Seto Inland Sea is one of the main sites for environmental remediation and restoration. Remediation and restoration carried out by different organizations in the Seto Inland Sea cover a variety of methods, depending on their objectives. Some examples include the simple restoration of tidal flats or seaweed and seagrass beds or a combination of tidal flats and seaweed and seagrass beds, artificial rocky shores, artificial lagoons, artificial submerged slopes, beneficial use of dredged sediments, and bird sanctuaries. Some typical examples of such activities are described below.

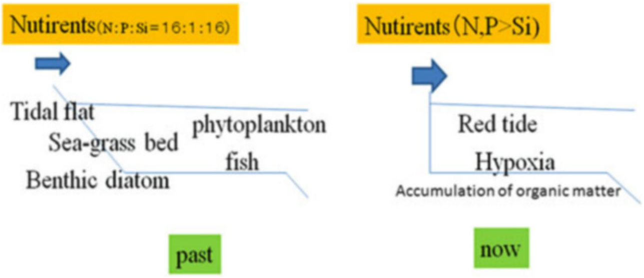


Fig. 3.53 Material cycling in the past (*left*) and present (*right*) in the Seto Inland Sea. Nutrient loads from the land increased with the change in N:P:Si ratio. Nutrients loads from the land were assimilated to benthic diatom, seaweed and seagrass, as well as the phytoplankton in the past but they were mainly assimilated to phytoplankton, and red tide and hypoxia or anoxia occurs now. Furthermore, the nutrient loads have begun to decrease in recent years

1. Very comprehensive habitat restoration is being conducted at the estuary of the Fushino River in Yamaguchi Prefecture, including the environmental remediation of the Fushino River watershed. Reforestation of the upstream area is also included in this project. A local currency, called Fushino, was introduced to the area in order to promote the project which was supported by the wide variety of stakeholders.
2. Etashima Bay in Hiroshima Prefecture has a highly enclosed topography and is an important ground for the culture of oysters. Oxygen depletion in the bottom water in summer and deterioration in sediment quality have been serious problems there. The local government of Hiroshima Prefecture initiated the restoration of Etashima Bay using a multi-sectoral approach in which five prefectural research institutes participated in the development of efficient tidal flats and seagrass beds in order to activate local fisheries and oyster culture.
3. Along the coast of Kansai International Airport, which is located on an artificial island in Osaka Bay, a gentle slope of natural rocks and stones rather than a vertically uplifted concrete wall was used in the construction of the airport. This environmentally friendly, gentle slope provided an appropriate site for seaweed beds and a suitable habitat for many kinds of organisms. As a result, this artificial structure is now working as a new seaweed bed and habitat. As the original site on which the airport was constructed was an area of muddy sea bottom, this is a good example of environmentally friendly, creative regeneration of the environment. Although the effect of the artificial island should be evaluated correctly, the effect of a more natural gentle slope itself should also be evaluated since the newly created seaweed bed plays a mitigating role in the widely lost seaweed bed in Osaka Bay.
4. At Mizushima-Nada in Okayama Prefecture, the water discharged from the dam is increased during summer when the precipitation decreases in order to increase material cycling in the coastal water because the decrease in river discharge results in a decrease in estuarine circulation and stagnant coastal water as shown in Fig. 3.54.

The above examples are described in detail in Yanagi (2012)

As to restoration of large-scale sea-sand mining effects, the environmental change is being monitored and the basic design for a restoration plan has been discussed by the Ministry of Land, Infrastructure, and Transport and the Fisheries Agency (http://seto-eicweb.pa.cgr.mlit.go.jp/rest/index.html), but practical restoration activities have not yet been achieved.

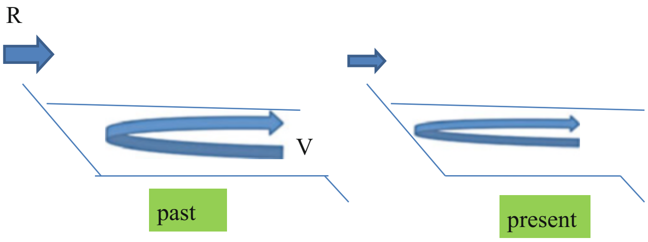


Fig. 3.54 River discharge and estuarine circulation in the past (*left*) and present (*right*) in the Seto Inland Sea. River discharge (R) has decreased due to dam construction and the volume of estuarine circulation (V) with a decrease in volume of R of about ten times; this may result in the occurrence of red tide and hypoxia

3.5.2 Future Direction

The results of the preliminary examination of the environmental health of the Seto Inland Sea made clear the deterioration in habitat conditions and ecosystem services. Hence, the restoration of such habitats in shallow water, including tidal flats and seaweed and seagrass beds, is one of the most pressing actions that needs to be taken in the Seto Inland Sea. Therefore, one of the major directions to be taken in the future should be the creative restoration and, possibly, the creative regeneration of a new Seto Inland Sea by the new governance system (Matsuda 2008).

A new concept, "Sato-umi", was proposed by the Research Institute for the Seto Inland Sea. In Japanese, "Sato-umi" means a coastal sea under the harmonization of sustainable, wise use with conservation of an appropriate natural environment and habitat (Yanagi 2007). Compared with a deteriorating coastal environment, "Sato-umi" is able to provide a higher biological diversity as habitat and higher biological production as fishing grounds. Such characteristics are also suitable for demonstrating the multifunctional roles of fisheries and ecosystem services.

Development of a new holistic approach for sustainable biological production and control of eutrophic levels is a prerequisite for establishing functionally efficient "Sato-umi" in each local coastal area. It is recommended that the promotion of integrated environmental management aimed at environmental remediation and restoration of a wide variety of habitats be undertaken in the near future under the new governance system that includes the central government. local government, and a wide variety of stakeholders such as fishermen, navigators, tourist companies, environmental NPO, and so on. This should involve the international exchange of information, ideas, and methodologies.

However, with respect to the future direction of habitat conservation and resource management, top priority should be given to the original objective. In the case of seaweed and seagrass bed restoration, this includes the high performance restoration of seaweed and seagrass beds. However, other viewpoints are also important. Future methods of habitat restoration and resource management should be examined from the viewpoint of low environmental impact, high recycling of material used, low cost with high cost performance, energy saving technology, and applicability of adaptive management. Continuous monitoring after restoration activities is also very important in evaluating the effectiveness of the restoration methods that have been used.

Important and practical future directions are itemized below:

Active conservation of a new environment in the Seto Inland Sea
- Preferable habitat environments and recreational spaces to recover seaweed and seagrass beds, tidal flats, and other shallow water areas must be restored.
- The strict control of reclamation and excavation must be done.
- Promoting fisheries from the viewpoint of the multifunctional role of fisheries to extract desirable ecosystem service.

Regeneration of forests, rivers, and the sea, with effective participation and partnerships among the various stakeholders
- Preferable water and material cycling, recognizing the interactions between forests, river basins, and coastal seas (watershed scale: ecosystem approach) must be established.

Establishment of mitigation systems
- Minimizing waste dumping in the area
- The wise and efficient use of vacant land along the coast
- Securing new environments in areas that are disappearing but of historical significance to recover their ecosystem service

Integrated coastal management (ICM)
- Wide-ranging cooperation among the national government, local governments, local citizens, companies, and other entities. A unified authority to be organized with all rights on management of the Seto Inland Sea

In conclusion, the development of a new holistic approach for sustainable biological production and control of eutrophic levels, or a kind of new creative restoration to recover the many kinds of ecosystem services of the Seto Inland Sea, is a priority. Promotion of integrated environmental management, including watershed management, should be adopted from the viewpoint of interrelated water and material cycling in the river basin, forest, and coastal seas. The concept of "Sato-umi", originating from the traditional ideas of the local people for the wise and sustainable use of coastal areas, can support this new creative restoration of the environment and habitat in the Seto Inland Sea.

Box 3.1: Rehabilitation of Eelgrass Beds by Fishermen

The area of eelgrass beds in the Hinase coastal sea area (the central part of the Seto Inland Sea) decreased after the early 1960s, mainly because of an increase in turbidity and use of agricultural chemicals on land. 590 ha of eelgrass beds in 1945 decreased to 12 ha by 1985 (Fig. Box 3.1). The fish catch by set nets of the Hinase Fishermen Union also decreased at the same time. The fishermen thought that the main reason for the decrease in the fish catch may have been the result of a decrease in eelgrass beds. Fishermen in the Hinase Fishermen Union began the rehabilitation of eelgrass

Box 3.1 (continued)

beds by gathering seeds of eelgrass from the remaining eelgrass beds in spring, preserving them until autumn and scattering the best seeds in late autumn from 1986 on. They have continued this activity for more than 30 years and the area of eelgrass beds expanded to about 80 ha by 2005 and the fish catch by set net also recovered (Fig. Box 3.2). Some local citizens have joined in this activity since 2011 because they believe that the preservation of the marine environment by expanding the area of eelgrass beds is very important for a healthy marine environment in the Seto Inland Sea.

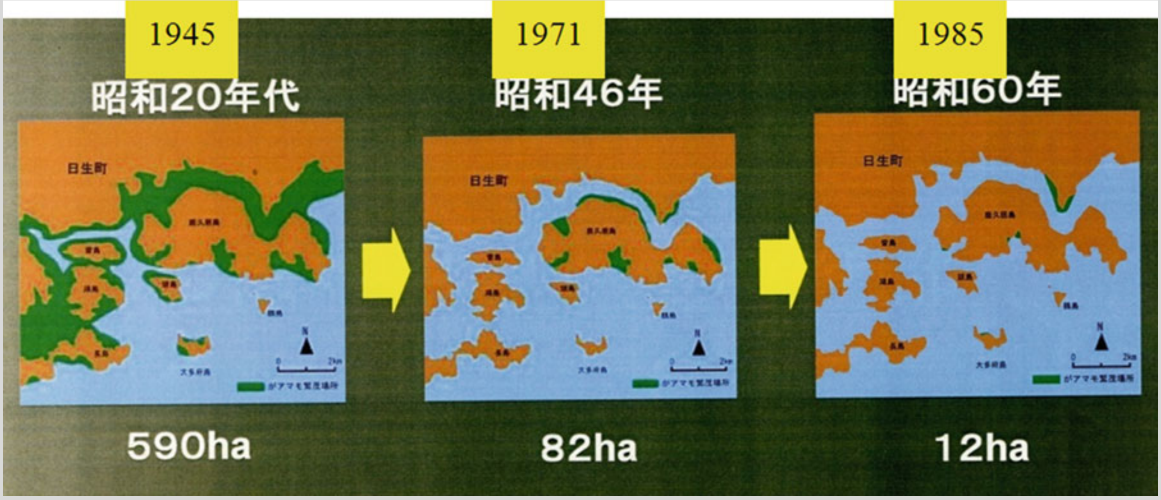


Fig. Box 3.1 Year-to-year variation in the area of eelgrass beds in the Hinase coastal sea

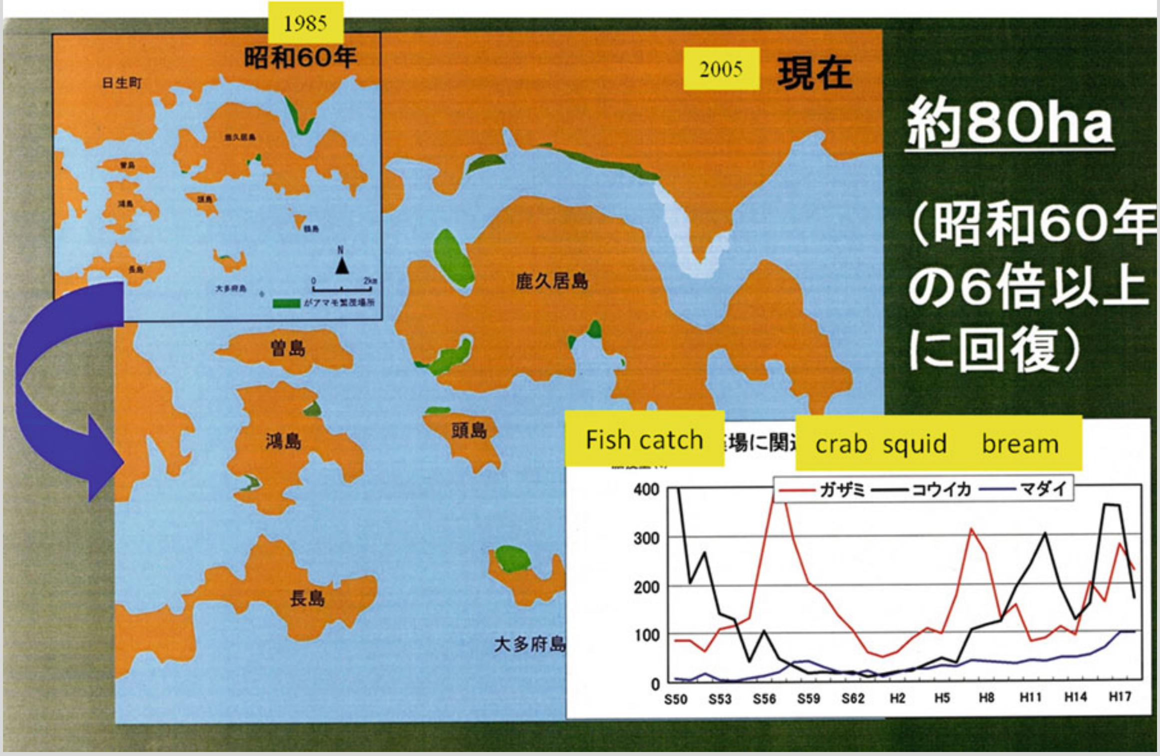


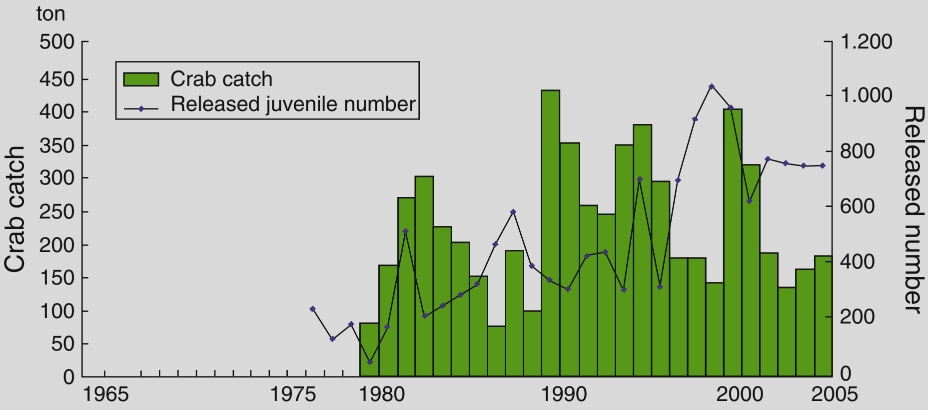
Fig. Box 3.2 Restored eelgrass beds in 2005 and year-to-year variation in fish catch by set nets

Box 3.2: Preservation of Swimming Crab Resources

Young fishermen engaged in the swimming crab fishing in the Tsunemi Fishermen Union (western part of the Seto Inland Sea) became concerned about the decrease in the crab catch after 2001, although they have released many young crabs each year (Fig. Box 3.3). They decided to perform resources management for the crabs under the suggestion of fishery scientists. They began such management by buying swimming crabs with eggs caught in the early summer and released them into the sea, from May 2004 onwards. They obtained funding of one million Japanese yen (approximately 10,000 US dollars) in 2004 to buy such crabs from the Fisheries Basic Fund, Fukuoka Prefecture. The crabs were cultured in water tanks on land, marked with "Do not catch" on their back using permanent marker pens, and were then released into the sea the next day (Fig. Box 3.4). If these crabs were subsequently caught again, the fishermen released them as soon as they saw the mark on their backs. The price was 500 yen per crab, which was half the market price for swimming crab measuring 16 cm (average size at that time of the year), and it was decided to be the same for all caught crabs irrespective of their size. They asked for cooperation in their attempts at resources management from local fishermen and buyers in the market; thus, the buyer did not buy crabs marked "Do not catch". The target of 2000 caught crabs was achieved in the middle of July 2004. No marked crabs were seen in the market that year. Such activities are still carried on. The catch of swimming crab increased from 127 t in 2003 to 155 t in 2004, to 175 t in 2005 and 206 t in 2006 as the result of this project (Fig. Box 3.3).

Fig. Box 3.4 Marked swimming crab with eggs purchased for release

Fig. Box 3.3 Year-to-year variation in the number of swimming crab juveniles released and their catch



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