Benthic Faunal Succession in a Cove Organically Polluted by Fish Farming

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In the past two decades, fish farming using net cages has developed in the coastal waters throughout Japan. Such fish farming has allowed the production of large amounts of valuable fish and their supply to the markets in major cities on a regular basis. However, fish farming is often followed by serious organic pollution of the water and bottom sediment in the vicinity of the cages since approximately 90% of the food for the fishes results in organic discharge to the environment around the fish farm. Organic pollution of soft bottom sediment is apt to be accompanied by the development of reducing conditions in the sediment and deoxidization of the bottom water, as a results of the decomposition of abundant organic matter. The benthic communities in such organically polluted areas are subject to catastrophic environmental disturbances. We have assessed the environmental conditions and abundance of benthic communities in a specific cove since 1966. The results of the present study clearly show the dramatic changes in fauna and the reduction in the abundance of members of the benthic communities in the cove that have accompanied the progress of the organic pollution associated with fish farming.

Coastal waters are areas with some of the highest rates of primary production, not only in terms of marine systems but also on the terrestrial biosphere (cf. Mann 1973). These areas have sustained the life of abundant and diverse marine organisms. For the human community, the coastal areas are also convenient, useful and suitable places for habitation. These areas have been exploited and modified by various human activities, and these activities have resulted in various levels of environmental disturbance of the natural ecosystem. In this report, we focus on the environmental disturbance that has resulted from organic pollution by fish farming in a specific cove. A general pattern of benthic faunal succession along a gradient of organic pollution of the sediment was found by Pearson & Rosenberg (1976, 1978). Benthic communities in healthy areas are diverse, and large organisms with shells, such as molluscs, echinoderms, and crustaceans, are abundant. As organic pollution of the sediment progresses, such benthic communities are gradually replaced by simpler ones which consist of organisms without shells, namely, polychaetes. In the most heavily polluted areas, the occurrence of hypoxic conditions in summer often results in temporary defaunation (Kolmel 1977, Tsutsumi & Kikuchi 1983). The benthic communities in such stressed areas are apt to be occupied by only several species of small capitellid and spionid polychaetes (Person & Rosenberg 1978, Reish 1979). In the present study area, Tomoe Cove, fish farming with floating net cages has been carried out since 1973. Red sea bream (*Pagrus major*) are reared in the cages, and approximately 1,300 tons of anchovies are fed to these fishes every year. Fish faeces and unutilized food residues disperse or sink down to the bottom, resulting in a very large discharge of organic matter to the bottom water and sediment of the cove. We have studied the seasonal fluctuations in physico-chemical conditions of the bottom water and sediment, and the abundance of members of the benthic community, in this cove since 1966 (Kikuchi & Tanaka 1976, 1978, Tanaka & Kikuchi 1978, 1979, 1980, Tsutsumi & Kikuchi 1983). The chemical conditions of the water and the sediment in the areas adjacent to the fish farm have been assessed by the fishery experimental station of Kumamoto prefecture since fish farming was initiated in the cove in 1973 [as reviewed in The fishery experimental station of Kumamoto prefecture (1973 to 1989)]. In this report, we describe the dramatic changes in fauna and the decline of benthic communities that are due to the organic pollution of the bottom water and sediment by fish farming, including the results of previous studies and unpublished data, and we discuss the association of fish farming with organic pollution and benthic ecology in organically polluted areas.

Study area

Tomoe cove is a subsidiary cove of Tomioka Bay which is located on the northwestern corner of Amakusa Shimoshima Island on the west coast of Kyushu, Japan (32° 32' N, 130° 02' E; Fig. 1). The cove is semi-enclosed by a narrow sand spit and its mouth is shallower than the cove itself. The influence of bay water on the cove is minimal. The bottom sediment can be separated into two types: the homogeneous muddy bottom inside

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the cove, and the sandy mud or fine sandy substratum at the mouth and outside the cove (Tsutsumi & Kikuchi 1983). The fish farm is located in the eastern part of the cove (shaded area in Fig. 1).

Methods and Materials

10 sampling stations have been set up for the routine assessment of the bottom environment and benthic communities in Tomoe Cove (Fig. 1). Samplings were carried out at 7 stations (Stn 1 to Stn 7) monthly from April 1966 to April 1967 (Kikuchi & Tanaka 1978), at 10 stations monthly from April 1978 to April 1979 (Tsutsumi & Kikuchi 1983), and at 10 stations twice (April, August) in 1989 (unpublished). At Stn 2, the annual fluctuations in the chemical conditions of the water and sediment have been measured by the fishery experimental station of Kumamoto prefecture since 1973 [The fishery experimental station of Kumamoto prefecture (1973 to 1989)]. In this report, we provided the following data: the annual fluctuations in COD (Chemical Oxygen Demand) and total sulfide in the sediment from 1973 to 1989, seasonal fluctuations in dissolved oxygen in the bottom water from 1978 to 1979, and abundance and faunal composition of the benthic community in April 1966, April 1978, and April and August 1989.

Dissolved oxygen in the water was measured by Winkler's method. COD was expressed in terms of consumption of $KMnO_4$. Total sulfide was determined by use of an H_2S-absorbent column (Hedorotec, Kitazawa Sangyo, Japan). Samples of sediment , for the estimation of the abundance of members of the benthic community, were taken with an Ekman-Birge bottom sampler (15 cm x 15 cm or 20 cm x 20 cm). Four grab samples were collected at each station. Samples were sieved on 1.0-mm mesh screen, and the residues were fixed in a 10% solution of formalin that contained Rose Bengal.. The benthic animals were sorted, identified to species, counted and weighted.

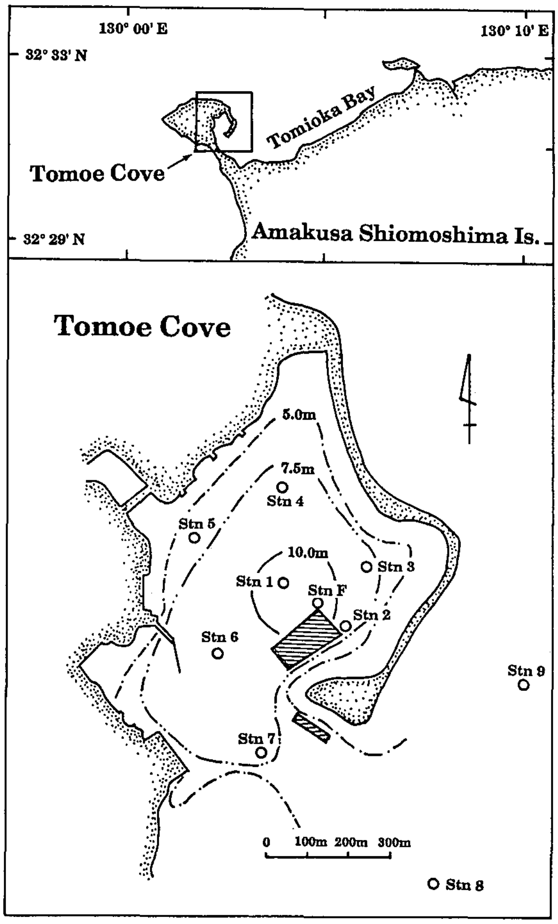

Fig. 1 Topography and bathymetry of the study area, Tomoe Cove. Hatched areas: cages used in fish farming.

Results

In Tomoe Cove, the organic pollution due to the discharge of organic matter from the fish farm is still in progress. Fig. 2 and 3 show the annual fluctuations in COD and total sulfide content of the sediment, respectively, at Stn 2. COD has increased linearly, and total sulfide has increased exponentially for the past 15 years. In 1989, the mean values of COD and total sulfide exceeded 32 mg/g dry sediment and 1.0 mg/g dry sediment, respectively. These data indicate that the organic matter from the fish farm has sunk through the water and accumulated on the sediment in the areas adjacent to the source of organic discharge, and that the increasing level of organic matter in the sediment has been associated with the production of larger amount of sulfides, including toxic hydrogen sulfide, in the sediment, as a result of the anaerobic degradation of the organic matter by sulfate-reducing bacteria. The bottom water in such organically polluted areas of the cove is apt to become hypoxic during summer, as a result of stagnation of the bottom water by stratification of the water column, accelerated degradation of abundant organic matter, and the oxidation of reducing substances in the bottom water and the surface sediment. Oxygen depletion in the bottom water has been observed in the areas adjacent to the fish farm in the cove (Stn 1, F, 2, 3, and 4) every summer since at least 1978 (Tsutsumi & Kikuchi 1983, Tsutsumi 1987, unpublished; Fig. 4).

The oxygen depletion of the bottom water in the cove resulted in the temporary disappearance of benthic animals (Fig. 5). In April 1989, benthic communities were abundant in terms of density in the cove. In particular, at Stn F and 3, the densities exceeded 10,000 m^{-2}. Nevertheless, in August 1989, benthic communities had almost disappeared from 5 stations (Stn 1, F, 2, 3, and 4). The benthic communities at these 5 stations have repeated an annual cycle of temporary defaunation in summer and a subsequent recolonization tn parallel with the recovery of benthic conditions from autumn to the next spring since 1978 at least (Tsutsumi & Kikuchi 1983, Tsutsumi 1987, unpublished).

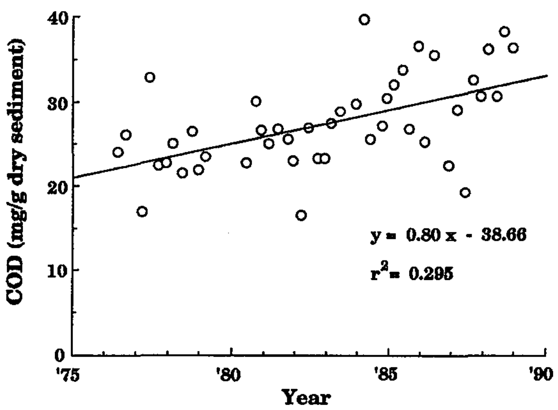

Fig. 2 Annual changes in COD of the sediment at St. 2. The data are based on the report: The fishery experimental station of Kumamoto prefecture (1973 to 1989).

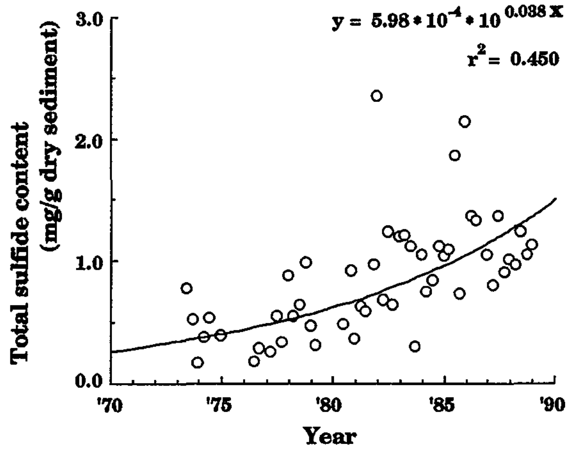

Fig. 3 Annual changes in total sulfide content of the sediment at St. 2. The data are based onthe report: The fishery experimental station of Kumamoto prefecture (1973 to 1989).

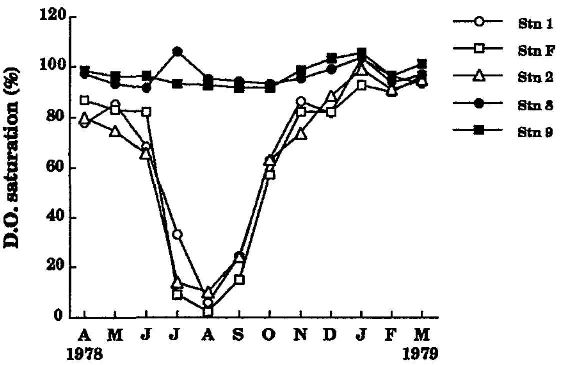

Fig. 4 Seasonal fluctuations in the percentage saturation with dissolved oxygen of the bottom water in Tomoe Cove (from Tsutsumi & Kikuchi 1983)

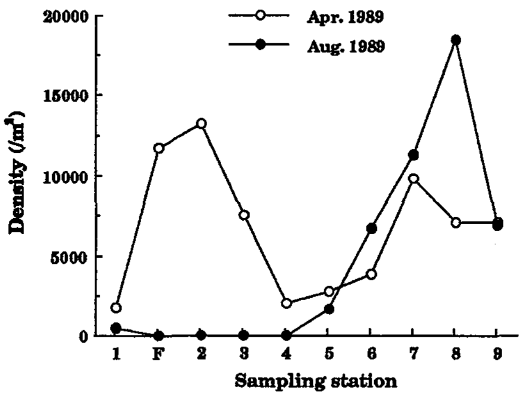

Fig. 5 Distribution of density of organisms in the benthic communities in Tomoe Cove.

The benthic communities in the cove are most populous in April to May just before oxygen depletion of the bottom water each year (Tsutsumi & Kikuchi 1983). The composition of the benthic fauna in April 1966, 1978 and 1989 has been compared to allow us to examine the association of benthic fauna with organic pollution by fish farming (Fig. 6). The faunal composition in 1966 represents that of the natural benthic communities in the cove before the benthic environment was disturbed by fish farming that was initiated in 1973 (Fig. 6a). Bivalves and gastropods predominated in the benthic communities. These molluscs accounted for 70% to 98% of the inhabitants of the benthic communities in terms of numerical composition at 7 stations in the cove. The faunal composition of benthic communities in 1978, when organic discharge from fish farm resulted in oxygen depletion of the bottom water and temporary defaunation in summer, changed markedly from that of the previous benthic communities. The majority of benthic fauna was replaced by polychaetes (Fig. 6b). In 1989, the numerical dominance of polychaetes further increased, and the composition percentage of polychaetes reached between 50% and 95% at all stations (Fig. 6c).

It is clear that, in the cove, as organic pollution progressed, the numerical dominance of polychaetes markedly increased in the benthic communities. Furthermore, a characteristic phenomenon was noted in relation to the increase in polychaetes in the benthic communities in 1989. At three stations (Stn 2, F, and 3), 60%, 67%, and 50% of the total number of individual organisms belonged to a single species of polychaete, *Capitella capitata*, and the densities were 7,000 m^{-2}, 8,800 m^{-2}, and 3,700 m^{-2}, respectively (Fig. 7). Therefore, this species was most representative of the benthic communities in the most heavily polluted areas adjacent to the fish farm. The changes in the benthic communities that accompanied the organic pollution were also clearly apparent in the biomass of dominant fauna. Fig. 8 shows the biomass of dominant fauna at Stn 1 in April 1967, 1978, and 1989. In 1967, the total biomass of the benthic community was 113 g/m^2 in wet weight, and two species of bivalves (*Musclista senhousia* and *Theora lubrica*) were the most dominant organisms in terms of biomass in the benthic community. The values, in terms of wet weight, for these two species were 55 g/m^2 and 15 g/m^2 respectively, and they accounted for 62% of the total biomass of the benthic community. In 1978, the total

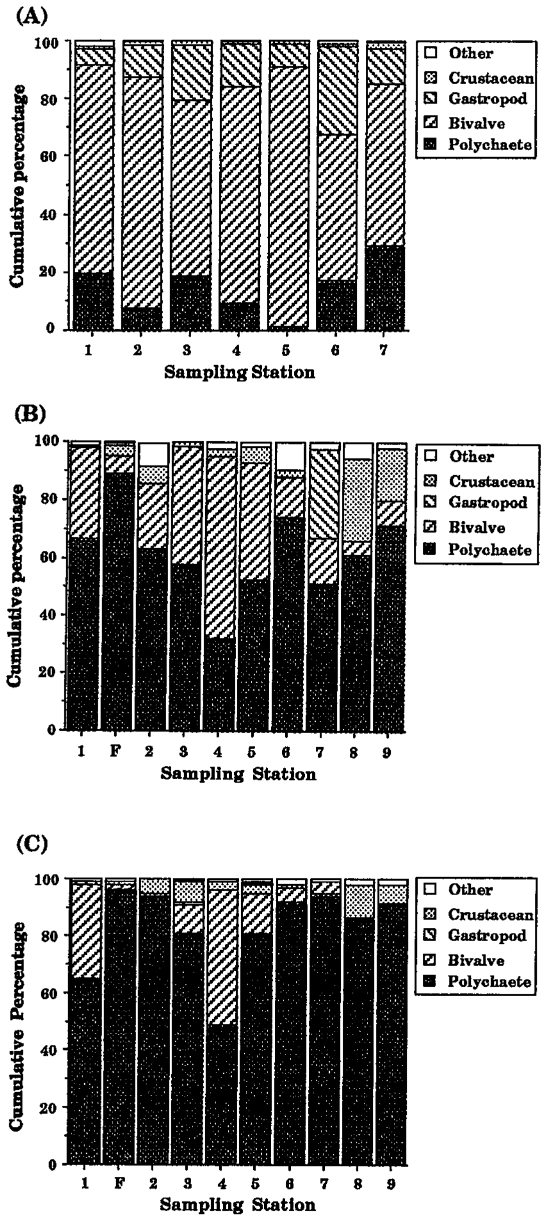

Fig. 6 Numerical composition of benthic communities, according to taxonomic group, in Tomoe Cove on April 27, 1966 (A)(the data are based on Kikuchi & Tanakna (1978); on April 28, 1978 (B)(data are based on Tsutsumi & Kikuchi (1983); and on April 28, 1989 (C).

biomass of the benthic community decreased to less than 25% of that in 1967 (26 g/m^2 in wet weight), and all molluscs except for one species of bivalve, *Theora lubrica*, disappeared from the benthic community. In 1989, the biomass of *Theora lubrica* decreased to approximately half of that in 1978 (8.7 g/m^2 in wet weight), and the total biomass of the benthic community decreased further to 11 g/m^2 in wet weight. In terms of numerical composition of benthic communities, the replacement of the dominant molluscs by polychaetes was found to follow the progress of the organic pollution of the cove (Fig. 6), However, t he biomass of polychaetes also markedly decreased from 30.0 g/m^2 in 1967 to 2.3 g/m^2 in 1989, since the polychaetes that predominated in the organically polluted areas were very small, for example *Capitella capitata*. Therefore, the domination by such small polychaetes of the organically polluted areas resulted in marked decrease in the total biomass of the benthic community. Thus, the total biomass of the benthic communities decreased by more than 90% in 22 years.

Discussion

The culture of red sea bream or yellow tail in floating net cages is one of the most common styles of fish farming in Japanese coastal waters. Fish farms are apt to be established in coves or bays with semi-enclosed topography so that the floating cages are protected from strong winds and waves. However, as shown in the present study, fish farming in such protected areas is often followed by organic pollution of water and sediment, due to the enormous discharge of organic matter from the fish farm itself and the minimal exchange of water. Fish farming requires that at least ten times the production of fish by weight is provided as food to the fish. This estimate is based on the ecological rule for the efficiency of transference of energy to the upper nutritional stages in the food chain. More than 90% of food is dispersed around the fish farm, or sinks down the bottom just below the fish farm, as unutilized food residues and excretion of fish. Fish farming using a floating net cage is associated with a major problem in its methodology, namely, most of the food for fish actually becomes organic discharge into the water and sediment in the vicinity of the fish farm. Therefore, it seems likely that the series of phenomena described in the present study area: oxygen depletion of bottom water (Fig. 4); high levels of total sulfide in the sediment (Fig. 3); temporary defaunation (Fig. 5); drastic changes in benthic fauna (Fig. 6 and 7); and a marked decrease in the biomass of benthic communities (Fig. 8), should occur frequently in association with fish farms with floating net cages in Japanese coastal waters. However, very few reports on organic pollution by fish farming are available. As shown by the results of the present study, fish farming itself imposes rather serious damage on the benthic ecosystem in the cove through the large organic discharge that it generates. The fish farm does not exist independently in the cove, but forms one part of the ecosystem in the cove through exchange of water to outside the fish farm. We can predict from the results of the present study that the fish farm in the present study area, Tomoe Cove, will itself be seriously damaged by organic pollution by itself in the near future.

Such disturbances of the benthic ecosystem in coastal areas are not caused only by fish farming, but also by various commercial activities throughout Japan on a much larger scale. For example, various water-front projects to exploit the coastal areas are always accompanied by physical modification of the topography of the coastal system, and the effluents from various factories and large cities result in the pollution of water and sediment by toxic substances, such as heavy metals, detergents, and organic materials, etc. Therefore, in the

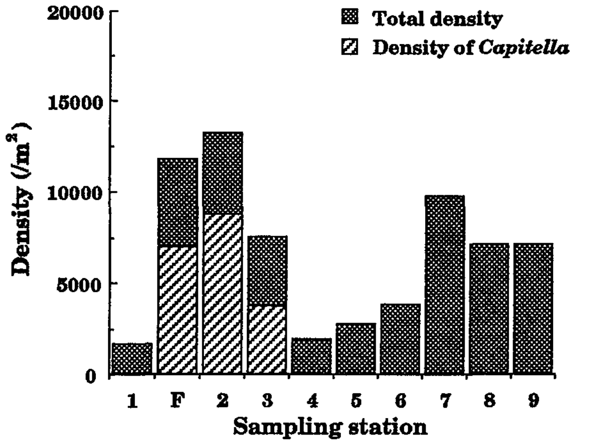

Fig. 7 Dominance of *Capitella capitata*, in terms of numbers of individuals, in benthic communities in Tomoe Cove on April 28, 1989.

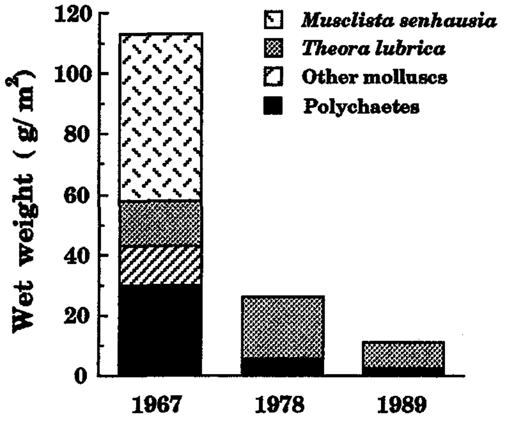

Fig. 8 Wet weight composition of the benthic community at Stn 1 in Tomoe Cove. The data for April 1967 are based on Kikuchi & Tanaka (1978), those for April 1978 are based on Tsutsumi & Kikuchi (1983).

recent years, catastrophic environmental disturbances and mass extinction of marine benthic organisms have occurred frequently in the coastal areas throughout Japan. Our benthic studies in Tomoe Cove appear to offer a model of a coastal benthic system that is seriously disturbed by organic pollution, even though the disturbance occurs in rather restricted areas. The results of the present study over two decades indicate that the changes in the benthic communities that accompanied the organic pollution of the cove coincided with the general pattern of distribution of benthic organisms along a gradient of organic pollution of the sediment described by Pearson & Rosenberg (1978). They very clearly demonstrated the decline of benthic communities and the replacement of organisms with shells to those without shells. The mechanisms that support the faunal replacement associated with organic pollution of the sediment were not adequately revealed in the present study. Grassle & Grassle (1974) suggested the advantages of organisms with opportunistic life histories (short life cycle, high potential for population growth and widespread dispersal ability) in disturbed habitats, and Tanaka & Kikuchi (1979) showed that early recolonization and rapid recovery of populations of benthic animals with short life cycles of less than 1 year and the extinction of population of those with rather long life cycle after temporal defaunation due to oxygen depletion of the bottom water. The most dominant species in the benthic communities in the organically polluted areas of Tomoe Cove is *Capitella capitata* (polychaete) in terms of density (Fig. 7) and *Theora lubrica* (bivalve) in terms of biomass (Fig. 8). Both species have a short life cycle and high potential for population growth (Kikuchi & Tanaka 1976, Tsutsumi & Kikuchi 1983, 1984, Tsutsumi 1987). However, the pattern of distribution of *Capitella capitata*, which occurs with high densities only in the most heavily polluted areas, is not explained only by its life-history adaptation to the disturbed habitats. *Capitella capitata* requires the organically polluted sediment itself, because of unidentified physiological characteristics (Tsutsumi 1990, Tsutsumi *et al.* 1990). Further studies on the benthic communities, population ecology and physiology of dominant species in the organically polluted areas will help to clarify the dynamics of benthic communities that accompany organic pollution and the association between replacement of benthic fauna with organic pollution of the sediment.

Acknowledgement

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