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A Direction Towards Sustainable Fish Feeding Culture with Least Material Loading in Semi-enclosed Seas

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Abstract

Although a diversified supply of fish is now required to support the recent increase in fish demand, fish culture, which is the second largest source of supply for fisheries, is facing a serious deterioration of water quality due to material loading by fish feeding. Establishment of fish feeding culture with least material loading has been tried by recovering the loaded materials with the help of useful organisms in Uranouchi Inlet, Kochi Prefecture, in the present study. Loaded dissolved matter, 62 % of total feed, is expected to be absorbed directly by phytoplankton, and loaded particulate organic matter, 28 % of total feed, will also be absorbed by phytoplankton in epilimnion during the period of vertical water mixing after decomposition to inorganic nutrients in hypolimnion. Phytoplankton are then fed to a filter feeder, the Japanese littleneck clam, followed by harvesting 3rd year clams over 30 mm in shell length from autumn to the next spring in order to establish a zero-emission type of fish feeding culture by recovering the loaded materials. It is estimated that loaded materials by current fish culture can be removed by maintaining an individual (ind) density of 2nd year or older clam such as about 1,000 ind・m^{-2}.

Key words: fish feeding culture, enclosed inlet, material loading, zero-emission, filter feeder, Japanese littleneck clam

1. Introduction

Looking back at human history, we have been mostly dependent on terrestrial animals and birds for sources of animal protein, but fish has not been utilized so extensively. People in the world, however, have recently increased their interests in fish for foods because of newly found diseases caused by viruses and prions from animals and birds which are extremely difficult to cure using current medical treatments, and because of recently pointing out the superiority of fish for human nutrition (Oshima, 2006).

Even though various wild animals, birds and plants were used greatly for human foods in the prehistoric era, much of the wild supply of human foods has not been continued because of insufficient supply of food materials due to rapidly increased human demand, and those terrestrial wild food supplies are now mainly used for game hunting and collecting wild plants for medicine or decoration. Almost all wild food materials supplied in the past are now replaced with food materials produced in agriculture fields and cattle farms under human care. On the other hand, fish are still harvested mainly from the wild. Due to a great improvement of fishing technologies such as "how to find catch" and "how to concentrate catch" in the 20th century, useful fish species have decreased in number throughout the world. Then people made efforts to find new fishing grounds and new useful fish species, which accelerated the decrease of stock of useful fish. If we continue the present trend, the decrease of stock occurring in useful fish species could accelerate, and result in collapse of the fishery industry in the world by 2050, which has been demonstrated by a persuasive study made by Worm et al. (2006). The present world fishery captures the marine life at a faster speed than the reproducibility of wild fish. As a result, human beings could harvest the complete stock of useful fish as we did for useful large mammals on the five large continents on earth in the past.

Because of the possible increase in demand for fish as an animal protein source for human nutrition in the future, as mentioned above, it is urgent to consider how to guarantee a constant supply of high quality fish for human foods while preserving a large diversity in species. For this realization, establishing various ways of increasing fish supply will be essential. The continua-

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tion of current fishery activities in regard to wild fish is unquestionably important, and sustainability needs to be strengthened (Takahashi and Ikeya, 2003). The most important point for sustainability of fisheries will not be to catch as many as possible, but to maintain the stock of wild fish thorough consideration of the structure and function of the ecosystem.

Since the wild fish catch cannot satisfy the present human requirements, fish supply by aquaculture cannot be discarded. In fact, the recent increase of the percentage share of cultured fish production in the entire fish production indicates the importance of aquaculture in fish supply (FAO 2008). For example, cultured fish production in Japan shared only 2.5 % of all fish production before 1990 but increased to 8 % in 2005 (MAFF 2008). However, the expansion of fish aquaculture has not always been easy and there are several essential difficulties. The first difficulty of possible expansion of fish culture will be the requirement for more human care and the resultant cost due to feeding duty because of the carnivorous of most marine fishes for culture, which results in choosing expensive fish species for culture and in limited production. The second difficulty is limited space available for culture in areas such as semi-enclosed seas because of the necessity for fish holding cages for culture to be set in semi-enclosed seas with high protection from storms and easy access from land.

At the same time, some problems occurring with fish feeding culture also serve to prevent the possible expansion of fish culture. One of them is material loadings supplied as wastes and excretions from fish feeding culture and attached materials onto fish cages, which could result water in low oxygen in the hypolimnion, and susceptible to forming red tides (Nishimura 1982, Gowen and Bradbury 1987, Wu 1995, Islam and Tanaka 2004). Huang et al. (2008a) has reported that 10-15 % of feed was recovered by fish with fish feeding culture of yellowtail and red sea bream, and the rest of 85-90 % was loaded to the environment. In addition, chemical loadings of various substances such as antibiotics and vitamins and anti-bio-fouling agents also cause a deterioration of water quality due to keeping an extremely high density of fish for culture in a limited space (Tacon et al. 1995, Wu 1995). Furthermore introduction of new diseases by juveniles in culture and perturbation of species diversity in the local ecosystem are other possible problems (Wu 1995, Elliott 2003).

It is then required to develop technologies for fish culture in offshore water (Hansen 1974) and on land under special consideration in order to minimize the negative effects of fish culture mentioned above (Tacon and Forster 2003).

As mentioned above, current fish feeding culture is confronting several difficulties in which the most serious two are feed and material loading. Since feed is mostly wild fish harvested in a large quantity, fish feeding culture cannot survive if fisheries collapse due to a large drop in fish stocks which could happen in the near future. On the other hand, minimizing material loading has been stressed for strengthening the sustainability of the fish feeding culture (Wu 1995), but there has not been any actual action plan yet. Materials loaded by fish feeding culture should be zero, or be recovered (zero-emission fish feeding culture). It will be a two-birds-one-stone solution if loaded materials are recovered by useful products. In the present study, current fish feeding culture has been challenged to enhance its sustainability by recovering loaded materials with useful organisms in Uranouchi Inlet, Kochi Prefecture.

2. Fish feeding culture carried out in Uranouchi Inlet

Uranouchi Inlet located in the middle of Kochi Prefecture is a narrow fjord type estuary having the surface area of 9.74 km^2, depths of 23-24 m at the center of main basin, an average depth of 7.8 m, and depths less than 5 m at the east end with a 0.26 km wide opening to the outside sea (Fig. 1). A sandy/mud bottom area having an area of 1.26 km^2 with depths shallower than 5 m is distributed mostly near the opening and partly in the main basin. The total volume of the inlet is 75.6×10^6 m^3, and volumes of shallower and depths deeper than 5 m are 38.9×10^6 m^3 and 36.7×10^6 m^3, respectively. There are 9 small rivers flowing into the inlet although total freshet is limited because of a limited water catchment area due to the steep hills around the inlet. Surface water temperature was recorded at the lowest of ca 11 °C in February, and increased slowly by April followed by accelerated increase after May, reached over 30 °C in August, showed a decrease down to 26 °C in October, and dropped to 14 °C in December (Fig. 2A, Huang et al. 2008b). Water mass became vertically stratified by the middle of May having thermocline at 1-5 m depth, and started to mix vertically in the middle of October by loosing its stratification structure due to a temperature drop down to ca 15 °C (Fig. 2B).

Feeding culture of yellowtail was started in 1970 using floating net cages (9 m × 9 m × 9 m in size for each cage) in the inlet, and feeding culture of red sea bream jointed in 1974. During the last 10 years, cultured fish production was recorded as large as 73.0-340 t (fresh weight, fw)·year^{-1} for yellowtail, 62.0-372 t (fw)·year^{-1} for red sea bream, and 170-569 t (fw)·year^{-1} for both fish species. Fish cages are set in the main basin which has a depth of ca 15 m, and 6 small culture areas of 9,477 m^2 covering less than 0.1 % of total inlet area were set in

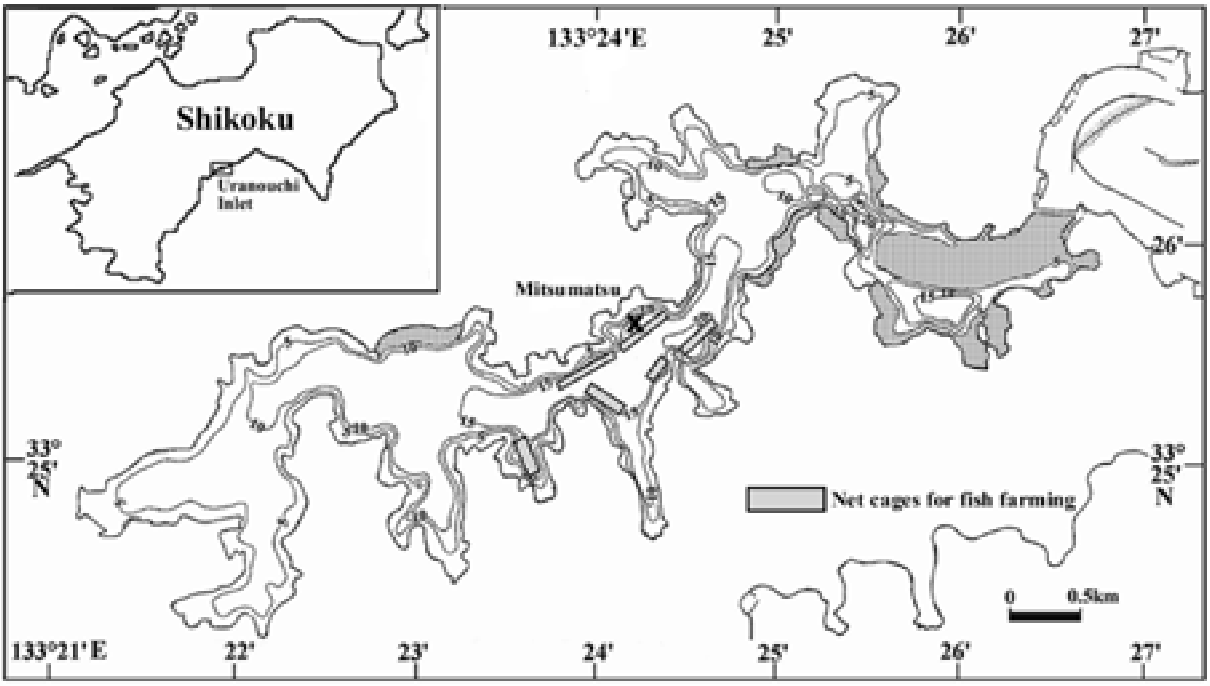

Fig. 1. Map of Uranouchi Inlet showing depth contour in meters. Closed squares indicate the areas for setting farming net cages. Dotted areas indicate sandy/mud bottom of less than 5 m in depth. "X" off Mitsumatsu represents the monthly observation point for determining various oceanographic parameters carried out by Kochi Prefectural Fisheries Experimental Station.

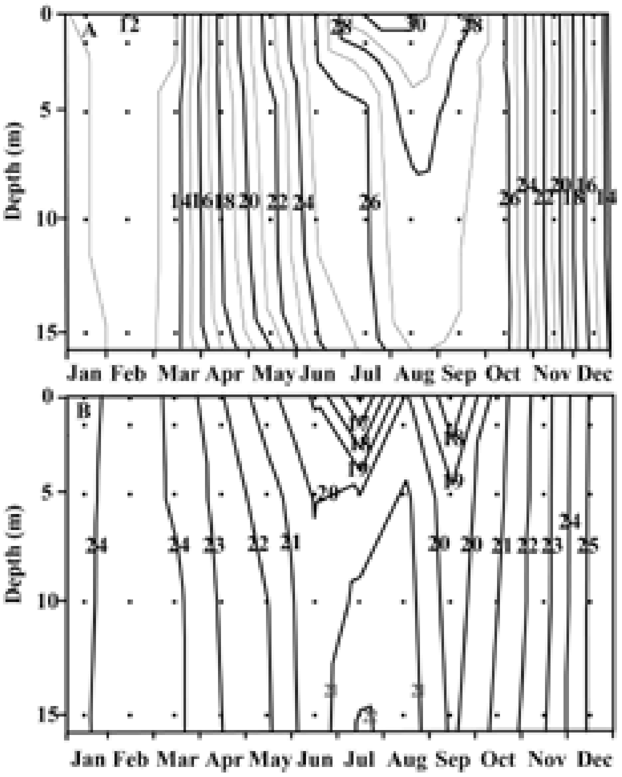

Fig. 2. Monthly vertical changes of temperature (℃) (A) and seawater density (σt) (B) in 2005 off Mitsumatsu, shown "X" in Fig. 1, in Uranouchi Inlet. (Plotted upon monthly fixed point observations by Kochi Prefectural Fisheries Experimental Station)

2005 (Fig. 1). Fish production per unit culture area was ca 0.6 t (fw)・year^{-1}.

In the inlet, yellowtail is cultured for 9 months starting from April by introducing individual juveniles of ca 10 g (fw) into net cages and by feeding them extruded pellets every year, and fish reaching ca 1,200 g (fw) are harvested in December. Total numbers of yellowtail for culture were ca 168,000 individuals. On the other hand, red sea bream is cultured for 20 months starting from May by feeding them dry pellets after the introduction of juveniles of ca 10 g (fw) into net cage, increases in size to ca 200 g (fw) by December, and reaches ca 1,000 g (fw) by the following December for harvesting. Total numbers of red sea bream were ca 620,000 individuals.

3. Material loading due to fish feeding culture in Uranouchi Inlet

Total rations for yellowtail, and 1st and 2nd year red sea breams were all concentrated from June to November, particularly from August to October, due to active fish growth, and the material balance of feeding showed consistent patterns both in ration and material loading except for an initial few months of juvenile stages (Huang et al. 2008b). Total yearly ration in Uranouchi Inlet in 2005 was recorded as large as 1,587 t (dry weight, dw)・year^{-1}.

Fig. 3 (Huang et al. 2008b) represents monthly changes in material loading due to fish feeding culture in

Uranouchi Inlet in 2005. Material loading from January to April was low, for example, 17.0-30.8 t (dw)·month^{-1} because of the low metabolic activity of fish at low temperatures and small fish sizes of 10 g (fw) as well as late introduction of fish in April for yellowtail and May for the 1st year red sea bream. Along with fish growth and accelerated fish metabolism with temperature increase, material loading increased rapidly from May, and reached a maximum of 234 t (dw)·month^{-1} in September followed by a decrease to 94.2 t (dw)·month^{-1} by December. Total material loading in Uranouchi Inlet in 2005 was 1,437 t (dw)·year^{-1} in which dissolved (DM) and particulate organic (POM) forms were 985 t (dw)·year^{-1} and 452 t (dw)·year^{-1}, respectively.

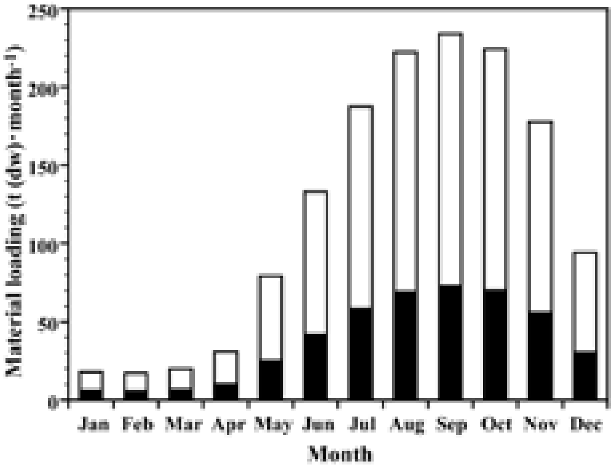

Fig. 3. Monthly changes of material loading due to fish feeding culture in Uranouchi Inlet in 2005. Solid column, particulate organic matter (POM); open column, dissolved matter (DM). (Huang et al. 2008b)

Assuming that the element composition of organic matter loaded by the current fish feeding culture is the same as that of organic matter in the sea proposed by Redfield (1934), the amounts of nitrogen and phosphorus loaded by fish feeding culture can be estimated based on carbon content as 35.8 % of dry weight, and molar ratios of carbon to nitrogen and carbon to phosphorus as 6.6 and 106, respectively (Fig. 4).

Most of excreted DM is in inorganic forms (Foster and Goldstein 1969, Gowen and Bradbury 1987), and inorganic nutrients such as nitrogen and phosphorus are essential (Fig. 4A). These nutrients will be diluted into the surrounding water and partly to the outside due to surface water movement such as by tidal currents, and the nutrients will be synthesized into organic matter by phytoplankton. Maximum loadings of dissolved nitrogen and phosphorus occurred in September for example, 10.1 tN·month^{-1} and 1.40 tP·month^{-1}, respectively, but daily loadings will be extremely small such as 0.00062 µMN·day^{-1} and 0.000038 µMP·day^{-1} if DM is dissolved completely in the surface water above 5 m. Assuming that primary productivity by phytoplankton in Uranouchi Inlet is higher than in the neighboring Tosa Bay (Ichikawa and Hirota 2004), nutrients at the levels of a few µMN·day^{-1} and a few 0.1µMP·day^{-1} will be easily absorbed by phytoplankton even at higher concentrations than those of homogeneously mixed mentioned above. A percentage of phytoplankton will be eaten by zooplankton and other filter feeders, and then fecal pellets will be settled out to hypolimnion as secondary loading.

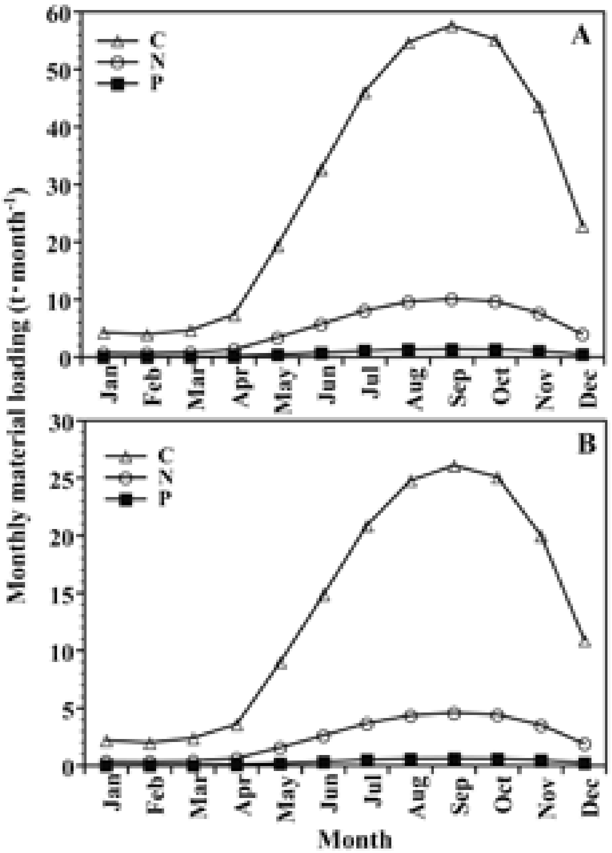

Fig. 4. Monthly changes of material loadings in carbon, nitrogen and phosphorus due to fish feeding culture in Uranouchi Inlet in 2005. (Estimated based upon Fig. 3) A, dissolved matter (DM); B, particulate organic matter (POM).

On the other hand, POM settling out underneath and near the net cage will be decomposed by using oxygen in hypolimnion (Fig. 4B). According to the estimated monthly consumption of oxygen during the stratified period (May to October) for decomposing the POM supplied to hypolimnion in Uranouchi Inlet (Fig. 5, curve of △; Huang and Takahashi 2008c), oxygen consumption increased from May and reached 87.1 tO_2·month^{-1} in September followed by a gradual decrease towards 36.2 tO_2·month^{-1} in December although that it was small such as 7.9 tO_2·month^{-1} from January to April. Considering the carbon contents in dry pellets was ca 44.3 % (Pawar et al. 2002) which was greater than 35.8 % of Redfield (1934) applied in the present study, oxygen consumption for oxidizing the loaded POM could be 19 % larger than the present estimate mentioned above.

Assuming that the in situ changes in dissolved oxygen below 5 m in the stratified water in the present inlet is represented by the point off Mitsumatsu, the maximum of 328 tO_2 was observed in February, decreased to 272 tO_2 by April, and further dropping to 146 tO_2 by June (Fig. 5). However dissolved oxygen below 5 m is maintained almost at a constant level followed by a rapid increase after September and recovering to 277 tO_2 by December.

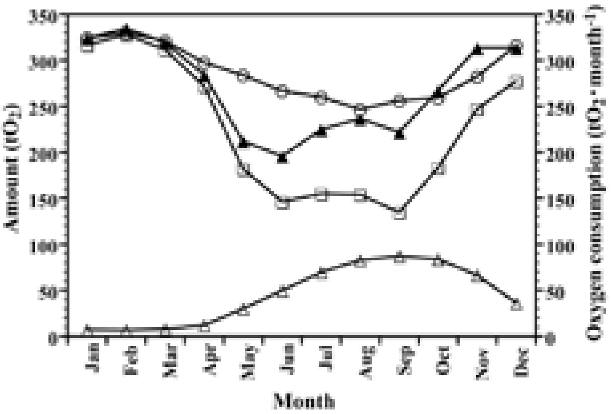

Fig. 5. Total amount of saturated dissolved oxygen (○), in situ dissolved oxygen (□), oxygen required for oxidizing particulate organic matter supplied by fish feeding culture(△), and □ plus △ (▲) below 5 m in Uranouchi Inlet in 2005. (Huang and Takahashi 2008c)

In situ dissolved oxygen mentioned above was added to the amount of oxygen consumption for decomposing the POM settled out to hypolimnion, and the results were shown graphically in Fig. 5 (▲). Probable time delay for decomposing organic matter was ignored. Results obtained showed that most of in situ oxygen consumption before April was probably due mainly to the other processes other than fish feeding culture because of extremely small supply of organic matter in fish feed during that period. After June, the curve showed almost constant increase which suggested possible oxygen supply occurring below 5 m. Saturated dissolved oxygen estimated at in situ temperature and salinity showed the highest at the lowest temperature of February such as 330 tO_2, and decreased almost proportionally with temperature increase towards August following with an increase again (Fig. 5).

As shown in Fig. 2B, vertical water stratification developed from June to October in Uranouchi Inlet, and then the water mass below 5 m was isolated from the surface water. Therefore POM settling out will be decomposed using dissolved oxygen in hypolimnion, and the resultant products by decomposition are expected to be accumulated in hypolimnion. Assuming that water mass in hypolimnion does not mix with the surface water as well as outside water, dissolved oxygen of 182 tO_2 contained below 5 m at the beginning of water stratification in May will be entirely used before the water stratification disappears. POM supplied to hypolimnion by fish feeding culture from May to October was 338 t, and oxygen requirement for complete oxidation will be 403 tO_2 (Huang and Takahashi 2008c). However decomposition of POM might not be completed during the water stratification period but be extended after October, because water temperature of hypolimnion in the stratified period from May to October was lower than the surface, for example, 20-28 °C. Decomposition of POM supplied to hypolimnion by fish feeding culture requires 2.2 times more oxygen of the total dissolved oxygen in hypolimnion during water stratification. When vertical water mixing occurs in November, decomposed products accumulated in hypolimnion will be mixed and diffused. This situation will be continued until the end of March. Since primary loaded POM was changed to inorganic nutrients (secondary loading) when it was returned to epilimnion by vertical mixing. Assuming that the total loading from May to October was mixed thoroughly by vertical water mixing, 21.3 tN and 2.9 tP will be supplied as nutrients to the surface.

As mentioned above, dissolved oxygen in hypolimnion could be consumed completely during the period of stratification (Fig. 5), however the actual decrease was only up to about a half of the saturated oxygen and stopped by June following with a constant oxygen concentration until September and rapidly recovery after October. Considering the saturated dissolved oxygen of 284 tO_2 for starting in May, the difference between the apparent dissolved oxygen in May and the saturated dissolved oxygen was 102 tO_2, where oxygen consumed for oxidizing organic matter will be ca 29.4 %. Similarly the proportions of oxygen demand for oxidizing loaded materials against to the apparent oxygen demand were obtained as 41, 66, 89, 72, 110, 189 and 93 % from June to December, respectively, in which the proportion was always fairly high with extremes of over 100 % in October and November. Munekage (1992) reported that there occasionally occurred frequent intruded water containing rich dissolved oxygen from outside sea, and recovered oxygen environment in hypolimnion. Huang and Takahashi (2008c) also recognized the probable invasion of outside oxygen rich water into the hypolimnion of the inlet at least once or more times per month from

July to September by analyzing monthly observation data. Consequently water in hypolimnion in Uranouchi Inlet seems to be supplied with oxygen by possible occasional invasions of outside water, which could explain no apparent oxygen consumption in the hypolimnion in the inlet from June through to September (Huang and Takahashi 2008c), and could be largely minimized the development of poor oxygen water due to oxygen supply from outside water. Otherwise it is highly possible that the water in hypolimnion of the inlet becomes anoxic.

Concluding the material loading due to fish feeding culture in Uranouchi Inlet, (1) DM mostly of inorganic nutrients were supplied into epilimnion mainly after May, showing a drastic increase from May to August and maintaining high loading until November, and giving more than half of the yearly loading from September to December (Fig. 4A). Yearly total loadings were 62.0 t for nitrogen and 8.6 t for phosphorus. (2) POM having similar loading pattern as DM was mainly loaded to the hypolimnion below 5 m (Fig. 4B), and was decomposed to inorganic nutrients followed by returning the nutrients to epilimnion by vertical water mixing after October. Therefore the most loaded materials supplied from hypolimnion to epilimnion were expected to be inorganic nutrients. Materials originally supplied as POM amounted to as large as 28.5 t for nitrogen, and 3.9 t for phosphorus from January to December. In Uranouchi Inlet, there is a possibility that loaded materials to hypolimnion could be transported out to the outside seas with possible intruded water from the outside sea occurring occasionally during summer stratification.

4. Useful recovery of loaded materials by fish feeding culture in Uranouchi Inlet

Since inorganic nutrients loaded by fish feeding culture in Uranouchi Inlet were supplied mainly into epilimnion of depths shallower than 5 m, they can be absorbed smoothly by phytoplankton. On the other hand, loaded POM settling out to hypolimnion was impractical to be recovered directly by organisms in deep water of more than 15 m such as the present Uranouchi Inlet. Then possibility of recovery by phytoplankton was considered when the POM was returned to epilimnion in the forms of inorganic nutrients after decomposition during vertical water mixing in autumn.

Fig. 6 represents the monthly nutrient loadings into epilimnion, at a depth shallower than 5 m, in Uranouchi Inlet. Materials from the loaded POM were added as nutrients of secondary loading in November and December splitting into two equal amounts. So, it is obvious that material loadings in Uranouchi Inlet centered from May to December. Since efficient POM removal of some filter feeders has been pointed out by Cloern (1982), Japanese littleneck clam, a filter feeder, and one of the important fisheries products in Uranouchi Inlet (Kuwahara 1984, Taino et al. 2006), was evaluated as a possible solution in recovering the loaded materials by fish feeding culture through utilization of phytoplankton which absorbed nutrients as the following.

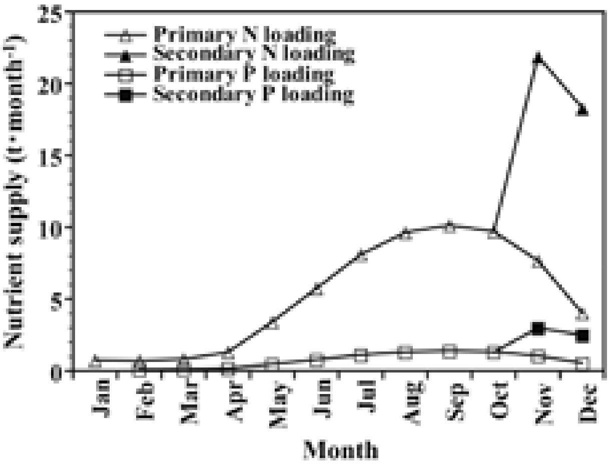

Fig. 6. Monthly changes of primary and secondary loadings of nitrogen and phosphorus due to fish feeding culture in shallower depths than 5 m in Uranouchi Inlet in 2005. (See details in text)

Japanese littleneck clams spawn twice, spring and autumn, in year in Uranouchi Inlet. Individuals spawned in spring have low survival rate due to lowered salinity occurring in rainy season before summer and high water temperature in summer, but those in autumn have a high survival rate and support the major clam population in the inlet (Kuwahara 1984). Autumn Japanese littleneck clam grows up to a size of ca 15-16 mm shell length by the end of first year, and reaches a harvesting size of ca 30 mm shell length with total weight of 8.2 g (fw) including shell by the end of 2^{nd} year. Increase of biomass of Japanese

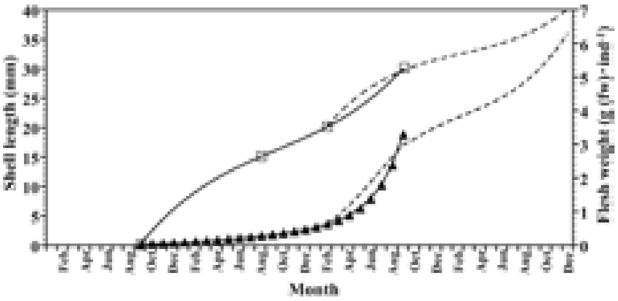

Fig. 7. Growth curves of Japanese littleneck clam in shell length (□) (Kuwahara 1984) and flesh weight (▲) (Robert et al. 1993) in Uranouchi Inlet. Dotted lines represent estimated curves for clam size of over 30 mm in shell length after Robert et al. (1993).

littleneck clam in Uranouchi Inlet was estimated from the growth curves of shell length and flesh weight shown in Fig. 7 where increase of shell length was firstly estimated after Kuwahara (1984) and shell length was then converted to flesh weight by using the data of Robert et al. (1993). Above a size of 15 mm shell length, survival rate reaches 100 % (Kakino 1996). Japanese littleneck clam could grow up to a size of 45-50 mm in shell length in the south of Kanto district (Toba 2005), and then the reported growth curve of clam in Uranouchi Inlet was extended over the size of 30 mm shell length according to Robert et al. (1993) in which it took 1 year to grow from 30 mm to 40 mm shell length as shown by the dotted line in Fig. 7.

Based upon the growth curve shown in Fig. 7, monthly growth of clam spawned in autumn was estimated (Fig. 8), where the solid line was applied until September of 2nd year and the dotted line was used thereafter. Actual growth of clam was fairly minimal from the initial September to January in the 1st year, but rapidly increased after that and particularly increased from April to August followed by a sudden drop after September. By representing the growth curve of clam with nitrogen and phosphorus weight, minimum requirements of those elements to support clam growth can be estimated. The following conversion factors were applied such as 40 % for flesh of total fresh weight including shell (MECSST 2005), 80.4 % for water content of flesh (Saeki and Kumagai 1980), 41.8 % for carbon content of dry weight (Kasai et al. 2004), 10.3 % for nitrogen content of dry weight (Kasai et al. 2004), and 1.97 % for phosphorus content of dry weight (after molar ratios of C/N and N/P reported by Redfield (1934) and Kasai et al. (2004)).

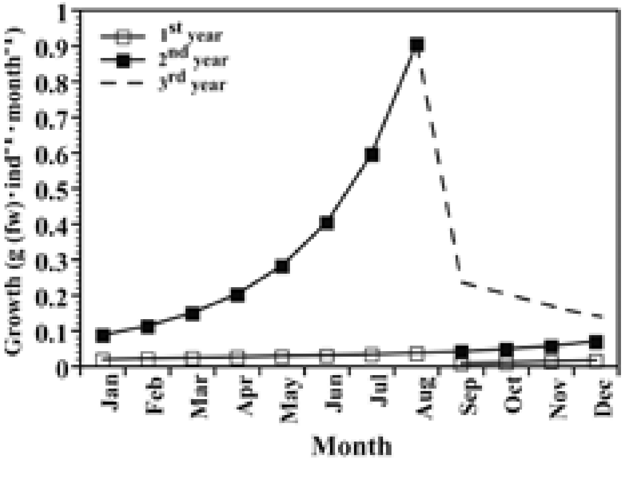

Fig. 8. Monthly changes of growth rate in fresh flesh weight of Japanese littleneck clam in Uranouchi Inlet. (Estimated based upon Fig. 7)

The 1st and 2nd year clams coexist from January to August, and the 1st, 2nd and 3rd year clams coexist in the rest of the months. Since material recovery by clams is highly dependent on shell size, most recovery can be made by the later stage of 2nd year clam. Assuming 1,000 ind·m^{-2} for the density of >15 mm shell size clam, because clam density was reported as high as 3,000 ind·m^{-2} in the south of Kanto district in Japanese islands (Kakino 1992), total clams of 12.6 × 10^{6} ind can be expected in shallow sandy/mud bottom of 1.26 km^{2} in Uranouchi Inlet if clams are equally distributed. Because the mortality of clams was high in sizes smaller than 15 mm shell length (Kakino 1996), special treatment is required for keeping the necessary clam density of 1,000 ind·m^{-2} in sizes larger than 15 mm shell length; such as how to obtain juvenile shells for maintaining the deficit of natural decrease, or how to supply >15 mm shell size clams cultured artificially. Consequently from September to December, three year classes of clam with densities of >1,000 ind·m^{-2} for 1st year, >1,000 ind·m^{-2} for 2nd year, 1,000 ind·m^{-2} for 3rd year and total of >3,000 ind·m^{-2} could be coexisting, and expected total density is >2,000 ind·m^{-2} with coexisting 1st and 2nd year clam from January to August.

Assuming that the later 2nd year clams are distributed at a density of 1,000 ind·m^{-2} in the entire sandy/mud bottom of Uranouchi Inlet and they maintain the growth rate shown in Fig. 8, recovery of nitrogen and phosphorus by clams was estimated and shown graphically in Fig. 9. From January to August, recovery of nitrogen was nearly twice compared to the loaded nitrogen, and that for phosphorus was three times. However the estimated recovery after September dropped to 1/3 for nitrogen and to 1/2 for phosphorus. Such monthly discrepancies between recovery and loading of materials were asked to be taken care by the existing basic productivity of the ecosystem, and the following discussion will be carried out on a yearly basis.

Considering that the 3rd year clam in January having an individual size of 31 mm shell length, flesh weight of 3.7 g (fw), dry weight of 0.72 g, carbon content of 0.30 g, nitrogen content of 0.074 g and phosphorus content of 0.014 g are all harvested, total expected yield is ca 9,163 t (fw) for whole clams with shell and 3,665 t (fw) for flesh, and recoveries of nitrogen and phosphorus are expected as 75.4 t and 14.2 t, respectively. Since the current yearly material loadings by fish feeding culture is 90.5 t for nitrogen and 12.8 t for phosphorus, phosphorus can be recovered completely but 17 % of nitrogen will be left.

Japanese littleneck clams are actually harvested in Uranouchi Inlet, and yearly yields were several 10 t until 1976 following with a rapid increase reaching 1,936 t in 1982 and 2,800 t of maximum in 1983 although it again declined to 78 t in 2003 (Kuwahara 1984, Taino et al. 2006). The present proposal for recovering the loaded

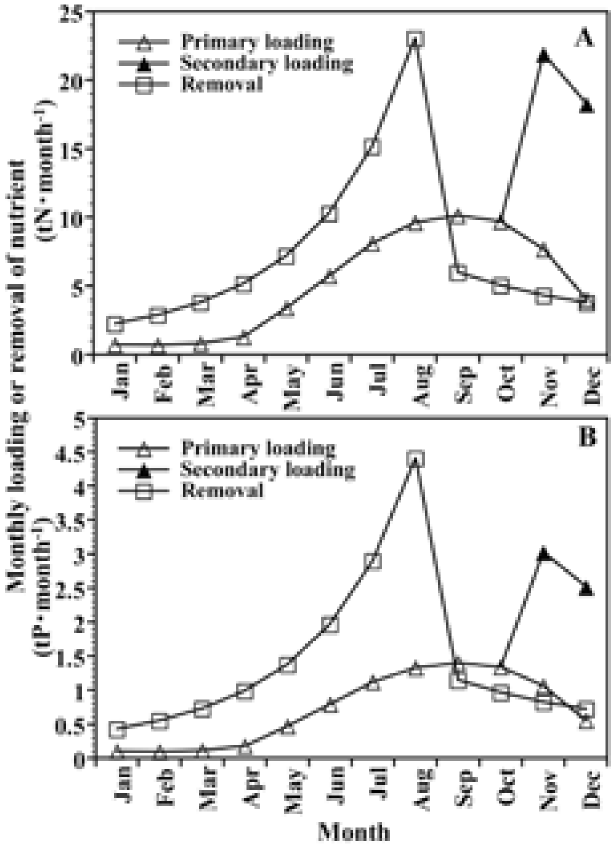

Fig. 9. Monthly changes of nutrient loadings in nitrogen and phosphorus (△, ▲), and their absorption by later age of 2nd year and 3rd year Japanese littleneck clam (□) under the assumption of individual clam density of 1,000 ind·m^{-2} in the sandy/mud bottom area of 1.26 km^2 with depths shallower than 5 m. A represents nitrogen, B represents phosphorus.

materials using Japanese littleneck clams requires at least 4 times more of the yearly maximum yield of clam on record, and then clam density in the inlet has to be increased extensively. Since clams have become less abundant compared to the past years in Uranouchi Inlet as observed almost throughout in Japan, special treatments are highly requested for recovering increased clam density under natural condition in Uranouchi Inlet or artificial supply of juvenile clams to meet the required clam density.

5. Sustainable fish feeding culture in semi-enclosed seas

Human activities carried out on earth having limited sizes of both space and activity are now strongly requiring zero-emission throughout our activities (Gunter 1995). A direction towards zero-emission of fish feeding culture has been challenged in the present study. Since the present trial was a case study focusing on current fish feeding culture conducted in Uranouchi Inlet, proposed material recovery by Japanese littleneck clam needs to be evaluated thoroughly before actual application. Furthermore there are also other possible candidates in organisms such as Japanese oyster, rock oyster and some seaweed like nori and sea lettuce, and there might be possibilities to be found in one single better species than the Japanese littleneck clam or combinated application of multiple species. For example, additional recovery of nitrogen of 5.1 t and extra removal of phosphorus of 0.68 t can be made if Susabi-nori, *Porphyra yezoensis*, is cultured during September to December in sandy/mud areas in a depth shallower than 5 m of 1.26 km^2 in Uranouchi Inlet.

The present attempt can be applied to other fields although suitable useful organism(s) has/have to be selected based upon the characteristics of actual material loadings and the environment. A similar situation could occur in Uranouchi Inlet if pattern and quantity of material loadings are changed in the future. To complete thorough zero-emission, life cycle assessment (LCA) involved in the entire fish feeding culture including production and consumption is highly requested. To do this, many factors including changes in our ways of thinking about environment are also involved. Therefore integrated efforts concerning research, administration, fish feeding culture industry, transportation, marketing, consumers and so on have to be considered.

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