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The 33rd UJNR Aquaculture Panel Symposium

Ecosystem and Carrying Capacity of Aquaculture Ground -for sustainable development of aquaculture and stock enhancement-

Seikai National Fisheries Research Institute, NAGASAKI 2-3 November 2004

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Keynote of the symposium The role of the fisheries industry as a supplier of healthy food for human has become more important in recent years. Marine aquaculture and stock enhancement have been developed and can now compensate the reduced productivity of the wild catch.

Aquaculture creates impacts on the surrounding environment and ecosystem in various ways. Intensive feeding fish-farming often results in adverse effects on both the fish farm itself and the ecosystem beneath and around the fish farm through changes such as oxygen deficiency, generation of hydrogen sulfide, and blooms of harmful plankton.

On the other hand, non-feeding aquaculture and stock enhancement of seaweeds and shellfish potentially prevent eutrophication by removing nutrients and particulate organic matter from the surrounding water. The integration of fish farming with non-feeding aquaculture is therefore a useful approach to mitigation of the environmental problems associated with marine aquaculture.

To achieve sustainable development of aquaculture, we need to deepen our understanding of the environmental problems associated with aquaculture activities, especially their effect on the ecosystem and carrying capacity of aquaculture ground. In this symposium we would like to discuss future perspectives of sustainable and responsible aquaculture, particularly in regard to the natural environment and ecosystem, methods of managing aquaculture grounds, and new approaches to integrated aquaculture management.

Ariake Bay − present conditions of fisheries and research for its restoration −

Tokimasa KOBAYASHI*

This theme is one of the symbol of a microcosm that includes many complicated issues related to social and scientific problems in the coastal fishery in Japan.

In Ariake Bay, the event occurred in 2000-2001 that the Porphyra (Nori) culture suffered from

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huge damage of discoloration by the environmental change for worse.

Many factors are included, such as oceanic condition, decreasing of current speed, rise of water temperature, reduction of concentration of nutrients, weakened wind blows, much rain by typhoon and after that sunshine lasted for a long time, and artificial matters, reclamation, dam, pollution etc. So briefly I introduce the research to restore the environment and fisheries production being done in the bay.

What is Ariake Bay？

Ariake Bay is located in northwestern Kyushu Island and a nutrient enriched productive sea. Its area is about 1700 square kilometers. The bay is semi-enclosed, being connected to the East China Sea through the narrow Hayasaki-Seto Strait. The bay environment is strongly influenced by the environmental conditions of the East China Sea (Fig. 1).

The main features of the bay are tidal flats, a large tidal range and enriched with nutrients. The tidal flats cover about 20,000ha along the coast of the Bay. Western part of the Bay is muddy sediment and eastern part is mainly sandy sediment due to the current direction counterclockwise.

Looking at from historical aspect, as the bay is shallow and flat tides are distributed widely, the reclamation had already begun in Shogun period to ensure the increase of food and protect their houses and farm from disaster. And after the world war two it was getting rapidly to solve the scarcity of food with the advance of technology. Until now about 26,600 ha, about 57% of the flat tide, had been reclaimed.

One more feature of the bay is the large tidal range. Fast tidal currents and strong vertical mixing have been observed in the bay due to the large tidal range (the maximum is about 6m) and shallow water depth (mean depth is 20m). Such a mixing process promotes oxidative decomposition of organic matter in the bottom layer and brings the regeneration of nutrients up to the surface from the bottom. This nutrient cycling provides a high productivity and has prevented bottom-water hypoxia in the inner part of the bay.

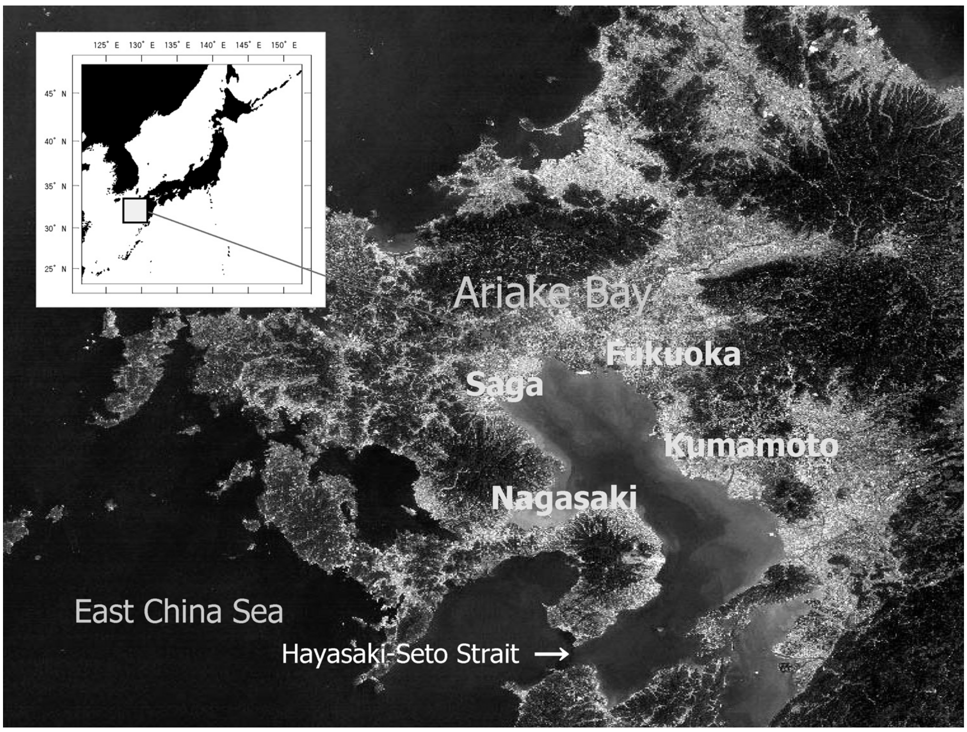

Fig. 1. Ariake Bay and adjacent area in north western Kyushu Island

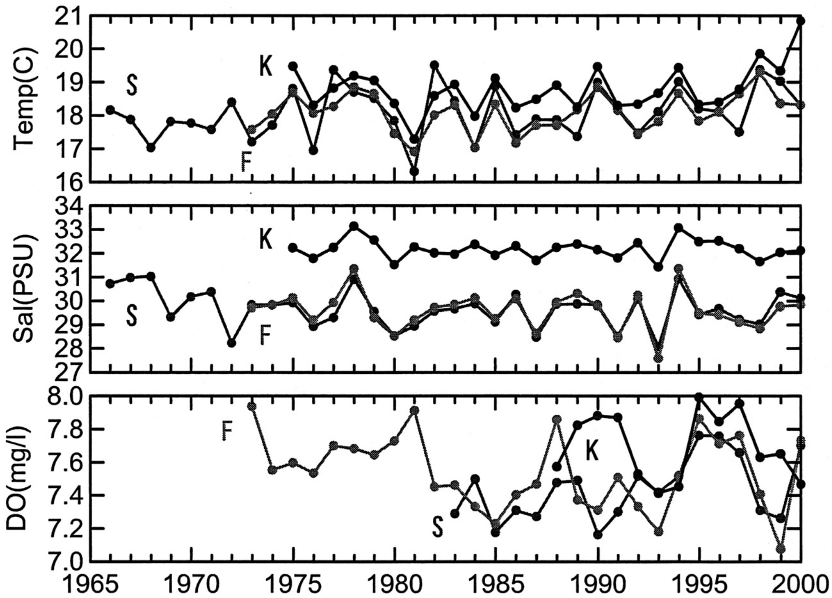

Fig. 2. Fluctuation of temperature (SST), salinity (PSU) and DO (mg/l) in Ariake Bay.
F : Fukuoka S : Saga K : Kumamoto

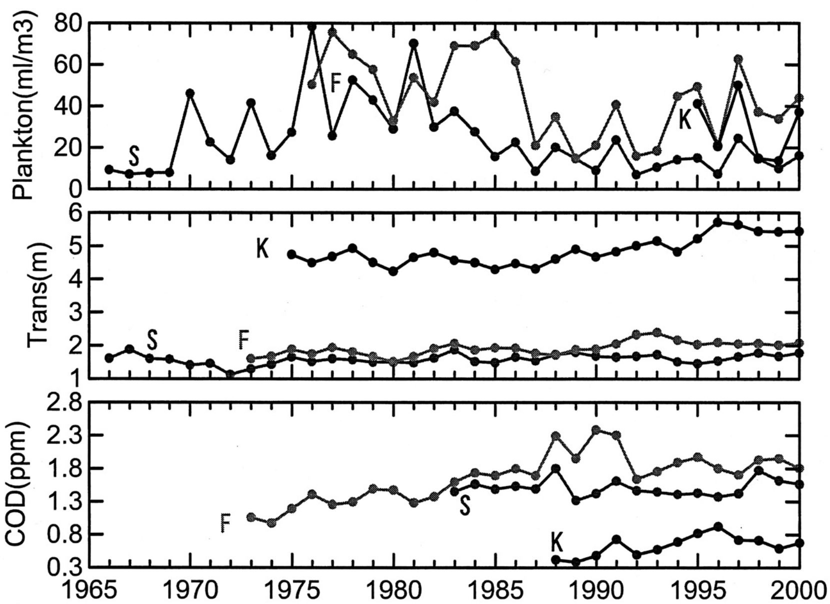

Fig. 3. Fluctuation of plankton (ml/m^3), transparency and COD in Ariake Bay.
F : Fukuoka S : Saga K : Kumamoto

Long term fluctuation of environmental indices

Water temperature is a well-used environmental parameter for fisheries grounds, higher water temperature than a normal year has been recorded at the bottom of the bay in recent years (Fig. 2).

The transparency has also been increasing. The area of muddy sediment has extended to the western part of the bay, where the sediment was formally sandy. Furthermore, COD is gradually increasing, implying the deterioration of the bay environment (Fig. 3).

The total number of the occurrence and the days of appearance of excessive algal blooms are rising in recent years. Particularly *Rhizosolenia imbricata* was appeared as a dominant species for a long time from September in 2000 to January in 2001. The reduction of nutrients by the algal bloom affected to the discoloration of Nori is estimated as one of the most important factor so far.

The tidal range has become also smaller, resulting from a decrease of the area of the tidal flats especially during neap tides. Moreover, hypoxia is formed in the inner part of the bay from early summer to late fall and the concentration of dissolved oxygen falls drastically especially during neap tides (Fig. 4).

Fluctuation of fisheries

1) Bivalves

The catch of bivalves was large and the major part of the fisheries in the bay. The amount of the catch reached more than 80,000 tons in the 1970s. Since then, however, the production of short-necked clam (*Ruditapes philippinarum*), jack-knife clam (*Sinonovacula constricta*) and pen shell (*Atrina pectinata*) has been diminishing. The catch fell to the level of 30,000 tons early in the 1990s, and it has further fallen to less than 20,000 tons in recent years (Fig. 5).

Following causative factors for decreasing yields of bivalves are considering;

1) Over fishing

2) Environmental deteriorations

a. Reductions in dissolved oxygen contents in water column

b. Blooms of toxic micro algae

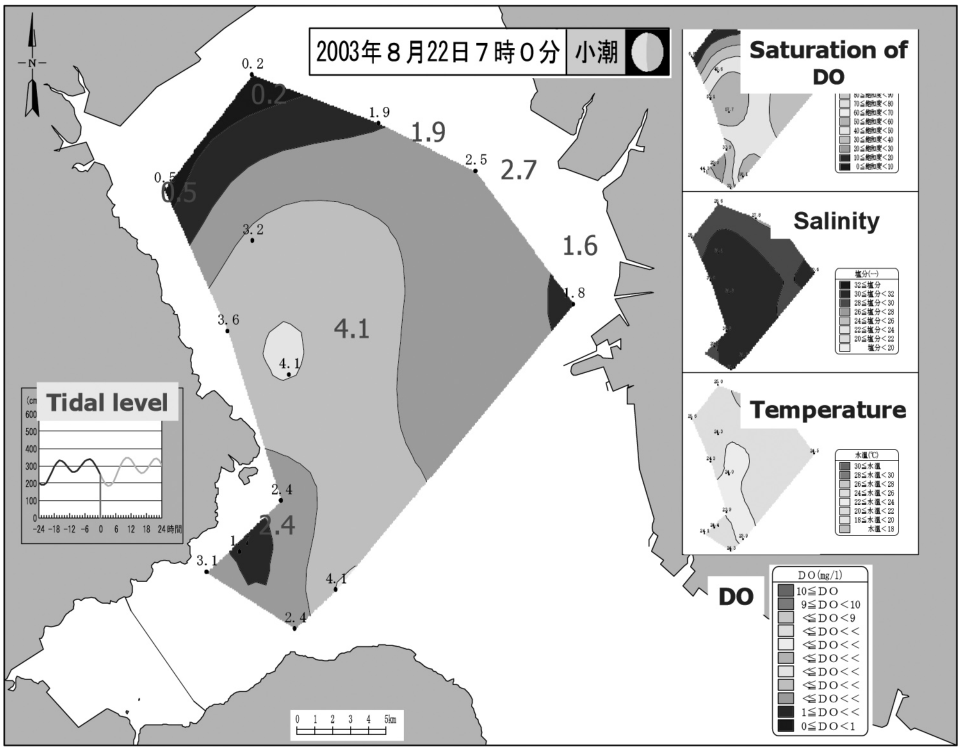

Fig. 4. Distribution of dissolved oxygen (mg/L) of bottom layer (−0.2～0.5m) at neap tide at 07:00 on Aug. 22, 2003.

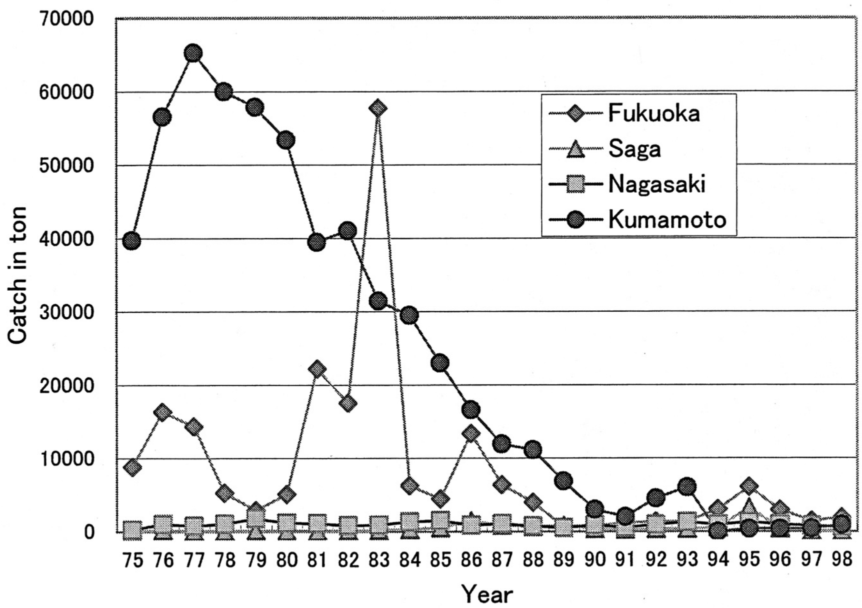

Fig. 5. Fluctuation of the catch of jack-knife cram in Ariake Bay

c. Unsuitable sediment conditions for larval settlement

3) Impact of predation

a. Predator such as crabs and rays

4) Outbreak of diseases

a. Protozoan and viral diseases

Particularly, mass mortality due to hypoxia was reported for jack-knife clam in the aquaculture grounds. And the predation by the ray, which inhabitants generally in southern waters, has also reported to be causing serious damage to the bivalve stocks.

One species of ray, *Aetomylaeus flagellum*, which eats two to three hundred of jack-knife crab per day was caught to decrease the damage more than eighty tons in 2003 in the bay.

2) Nori

The Nori production has been increasing since 1960's, and it reached 60,639 ton in 1970, 92,913 ton in 1980, 121,732 ton in 1990, and it reached the maximum of 168,250 ton in 2001. The production of cultured Nori in the bay occupies about 40% of the total amount of Japan. And its economic value is estimated about 40 to 45 billion yen in recent years.

However, discoloration of cultured porphyra was widespread in the winter of 2000-2001, damaging the porphyra production. The discoloration was thought to be caused by a shortage of nutrients as a result of the unusual environmental conditions such as a large amount of precipitation in the fall, longer daylight hours far exceeding normal years and repeated occurrence of atypical algal blooms. The production felt to 91,146 ton in that year. It showed the lowest value in the past 25 years (Fig. 6).

3) Fish and Crustacea

Commercially important fishes such as flat fishes, puffer and crustaceans such as blue crab are caught in the bay. However, their share in the total catch is small and the amount of catch has never exceeded 20,000 tons. Annual fluctuation is relatively small but a gradual declining tendency has also been noticeable in the 1990s (Fig. 7).

Present and future program

1. Monitoring

- Ocean environment (physical, chemical and plankton data)
- Harmful algal bloom (resting spore)
- Eggs and larvae distribution

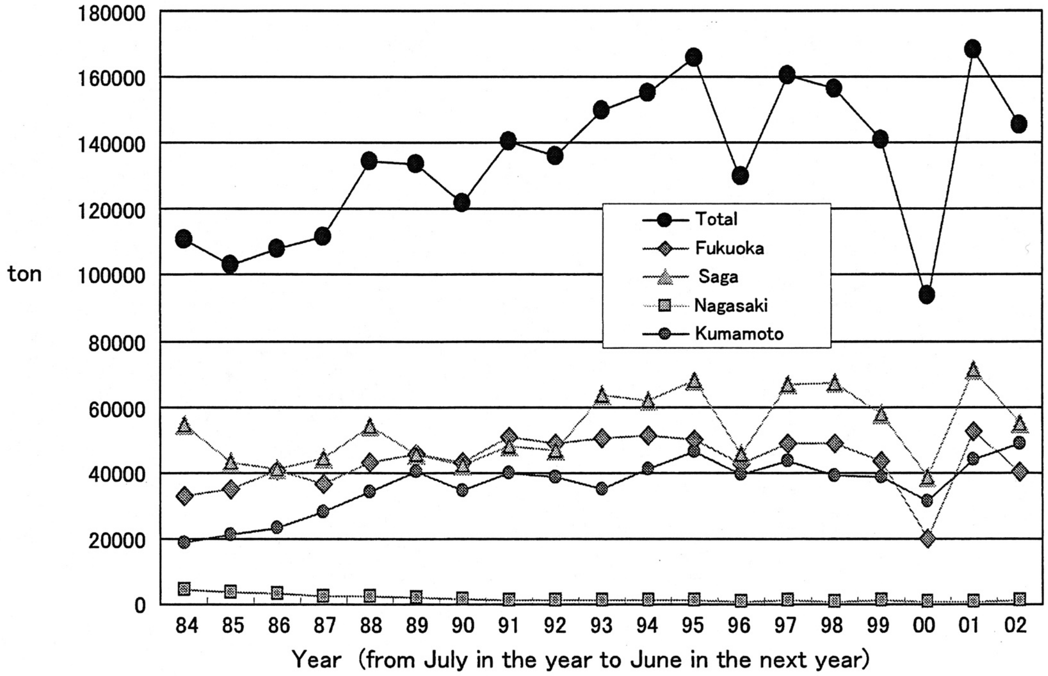

Fig. 6. Nori production in Ariake Bay

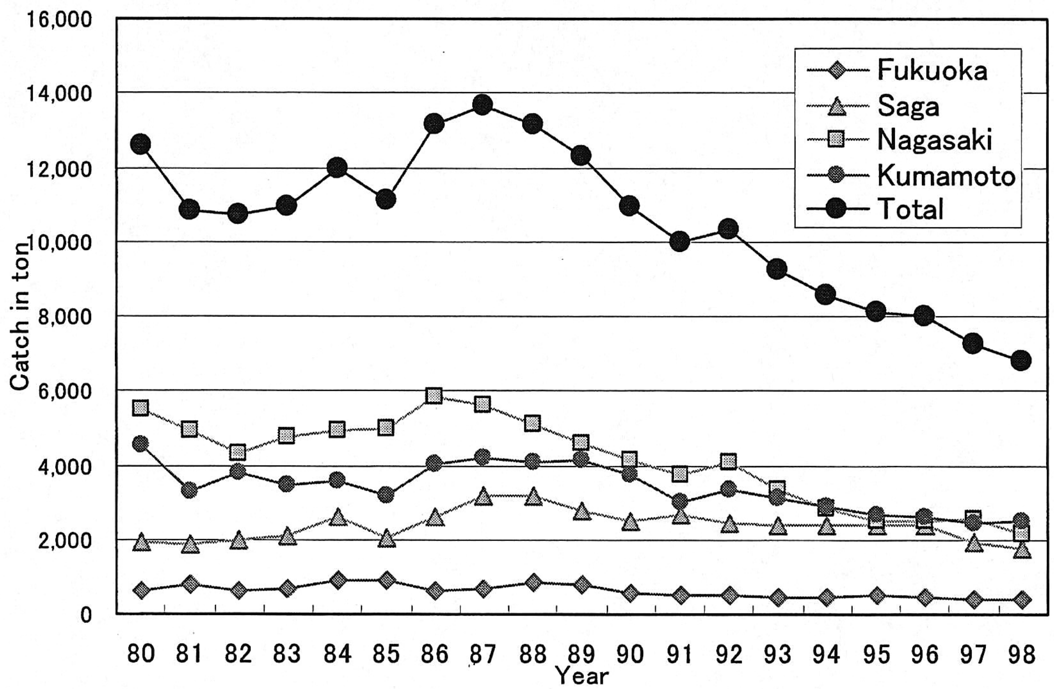

Fig. 7. Catch of the wild fish in Ariake Bay

・Hypoxia : mechanism of trigger technique of elimination

The bivalve catch and Nori production are undoubtedly the main fisheries production in the bay, but the production is not stable. Therefore, it is an important issue to restore the bivalve resources and to maintain the steady production of Nori. Additionally, it is requested to improve the habitat environment, especially quality of water and sediment. It is known that the improvement of sediment quality can be achieved by irrigation and/or covering by sand. More investigation of the effectiveness and long-term persistence of these methods are necessary and also trying to develop more effective techniques to restore the sediment environment is needed. And also investigating formation mechanisms of hypoxia is proceeding in order to find where hypoxic conditions will form, when they will form, how large an area it will affect, what will trigger hypoxia, and how to eliminate it.

Other related research includes a development of techniques to prevent harmful effects of excessive algal blooms on cultured Nori as well as to predict an outbreak of excessive algal blooms.

2. Restoration

・Release of seeds (fish, bivalve, shrimp, crab)
・Breeding (algae)
・Sediment quality (irrigation, covering by sand)

We also have strong research programs on seeds for release including fish and shellfish, breeding of high-temperature, low-nutrient resistance Nori in order to restore fisheries resources and to maintain sustainable fisheries in the bay. So it should be continued to monitor the present status and to be developed some techniques on the restoration. And it would be considered to synthesize the carrying capacity and production in the bay.

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Effects of resuspended sediments on the environmental changes in the inner part of Ariake Bay, Japan

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Abstract: Turbidity, *in situ* fluorescence of phytoplankton pigments and dissolved oxygen concentration were monitored and their relationships to tidal variations investigated in the inner part of Ariake Bay. Turbidity during spring tides showed large short-term variations due to the tidal resuspension of bottom sediments. The phytoplankton biomass increased from neap tides to before spring tides, because of the higher nutrient availability in the surface low salinity water caused by the stratification and the higher transparency due to the low turbidity. While during the spring tides, the increase of phytoplankton biomass was restricted by the low light availability due to the turbid water caused by the resuspended sediments, strong mixing with offshore water and possibly flocculation of phytoplankton with the resuspended sediments. During the neap tides in summer, large scale hypoxia was also observed in the offshore area of tidal flats, where resuspended sediments accumulate on the surface sediments. These observations indicate that the recent reduction of tidal currents is one of the contributing factors to the decrease of resuspension of the bottom sediments and increase in hypoxic areas within the bay.

Key words: Ariake Bay, resuspended sediments, phytoplankton, turbidity, tidal flats, hypoxia

Introduction

Ariake Bay (1,700km^2), located in the western part of Kyushu Island, is a shallow semi-enclosed estuary with maximum tidal range over 5 m in the inner part. The strong tidal current and large tidal flats areas are produced by the large tidal range. Bottom sediments are resuspended by the strong tidal current and high turbidity zone (up to 4,000 mg·L^{-1}) is formed around the tidal flats (Shirota and Kondo, 1985). Dynamics of resuspended sediments strongly influences on phytoplankton productivity through light availability (Cloern, 1987). Besides, mutual flocculation of phytoplankton and resuspended sediments leads to the removal of phytoplankton from the water columns (Avnimelech *et al*., 1982), by which large scale red tide was scarce in Ariake Bay (Shirota and Kondo, 1985).

However, red tides are frequently observed in recent years, especially in the winter season of 2000 to 2001 when the extensive bloom of diatom seriously damaged Nori (*Porphyra*; Rhodophyta) farming production (Watanabe *et al*., 2004). In Ariake Bay, increase of transparency from 1980s is reported, which seems to be caused by the reduction of bottom sediments resuspension (Tanaka *et al*., 2004). From 1980s, the gradual reduction of tidal amplitude and mean sea level rising are also pointed out (Takigawa and Tabuchi, 2002; Unoki, 2003), which was attributed to the topographic changes due to the reclamation projects and the effects of decrease of tidal amplitude in the outer sea. Those may reduce the bottom sediments resuspension. Moreover, hypoxia is formed in the bottom water in the inner part of the bay from summer to fall and the concentration of dissolved oxygen falls drastically especially during neap tides (Tanaka and

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Kodama, 2004).

In this paper, the results of continuous monitoring of turbidity, *in situ* chlorophyll fluorescence and dissolved oxygen in the inner part of Ariake Bay during the Nori farming season of 2002 to 2003 (Tanaka *et al.*, 2004) and summer 2003 (Tanaka and Kodama, 2004) were summarized and their relationships to tidal variations were discussed.

Materials and Methods

Data were collected using the towers constructed for observation of temperature and salinity for Nori farming (Fig. 1: T1-T4).

Light penetration was measured with an under water quantum sensor (ALEC MDS-MkV/L) at T4 (Fig. 1) in the north-eastern part of inner Ariake Bay (Chikugo River Estuary) on 25 Nov. 2003. At the station, measurements were taken every 10 min. at 0, 0.5, 1.0, and 1.5m depths to obtain data to calculate the attenuation coefficient (k). At the same time, turbidity was measured with a sensor (ALEC COMPACT CL/W) calibrated with suspended sediments concentration (SS: $mg \cdot L^{-1}$).

Continuous monitoring of turbidity, *in situ* chlorophyll fluorescence, salinity and temperature at 1m depth were carried out from 20 Sept. 2002 to 10 April 2003 at T4 located in the middle of the Nori farming ground in the Chikugo River Estuary (Fig. 1). Continuous monitoring of turbidity and dissolved oxygen in bottom water (0.5m above the bottom) in the inner part of Ariake Bay were made at 4 stations (T1-T4) from 9 July to 3 Sept. 2003.

Turbidity, *in situ* chlorophyll fluorescence and dissolved oxygen concentration (DO) were measured with Chlorophyll/Turbidity sensors (ALEC COMPACT CL/W) and DO sensors (ALEC COMPACT DO/W). They were set 1m depth using buoys or 0.5m above the bottom by attaching to the towers. Time series data were collected at 10 min intervals. Salinity and temperature data were collected by using a telemetry system and time series data of 1-hour intervals were obtained. Maintenance of instruments was carried out once or twice a month to clean up attached organisms on the instruments together with water sampling for

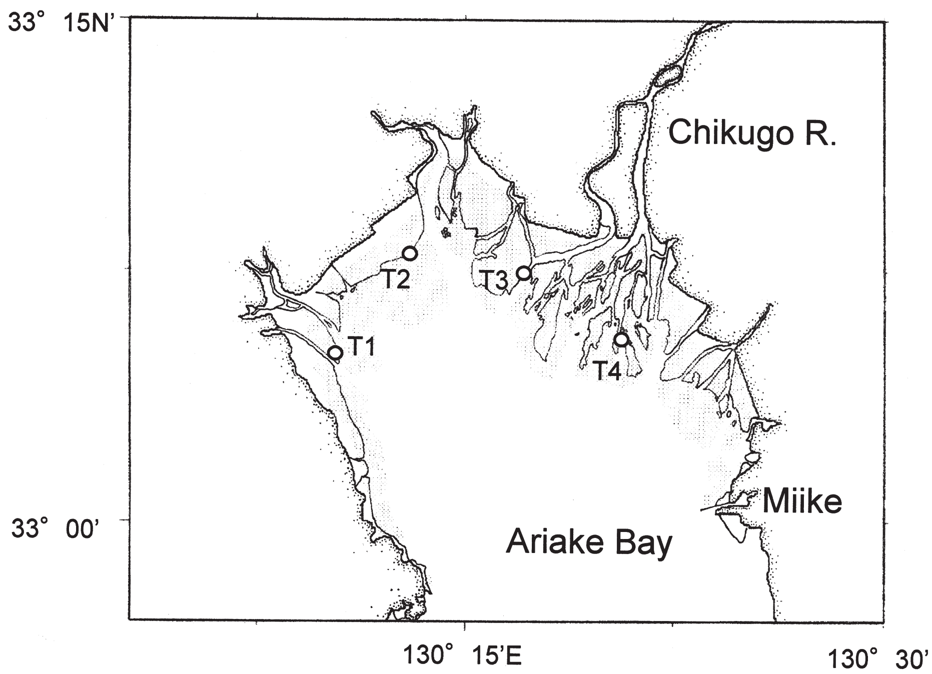

Fig. 1. Distribution of tidal flats areas and environmental monitoring towers for Nori farming in the inner Ariake Bay (T1-T4). Each station is located in the middle of the Nori farming grounds and outer edges of tidal flats.

calibration.

Water samples for calibration of instruments were filtered with Whattman GF/F filters and concentration of suspended sediments (SS) and chlorophyll pigments (chlorophyll *a* + phaeo-pigments) were determined. Relationships between SS and turbidity (NTU), and between chlorophyll pigments and in situ fluorescence were both linearly related as follows. [SS = 2.16 × NTU + 2.74, r = 0.99, n = 62], [Chl. *a* + phaeo. = 2.99 × (fluorescence) + 1.97, r = 0.92, n = 62]. These relationship curves were used to convert turbidity and fluorescence data to SS ($mg \cdot L^{-1}$) and chlorophyll pigments ($\mu g \cdot L^{-1}$), respectively.

Results and Discussion

Light limitation by the resuspended sediments

Fig. 2 shows linear regression of Light extinction coefficient against SS measured at T4. We obtained strong correlation (k = 0.062 × SS + 0.28 r = 0.98), which imply that light attenuation is primarily a function of suspended sediment concentration. Using this equation, we calculated the compensation depth (depth of 1% surface irradiance) from SS, assuming the vertically uniform SS distribution, which was commonly observed in the shallow well-mixed type estuary, such as the Chikugo River Estuary (Shirota and Tanaka, 1981). Fig. 3 shows variations in the tidal level at Miike (A), daily mean salinity and water temperature (B), in situ chlorophyll fluorescence (C), SS (D), daily average compensation depth (E), and chlorophyll pigments at high water (F) at T4(1m). The data of chlorophyll fluorescence and turbidity from 18 Oct. to 2 Dec. 2002 could not be obtained by the instrument trouble.

SS was higher during spring tides and lower during neap tides (Fig. 3(D)). During spring tides, higher SS was observed at low water while lower SS was observed at high water. These results indicate high turbidity water formed by the resuspension of bottom sediments in the upper reaches of the estuary was tidally transported to the offshore area of the tidal flats. In this manner, SS exhibited semi-diurnal variations during spring tides, however it was not clear during neap tides. During spring tides, variations of *in situ* chlorophyll fluorescence exhibited similar pattern to SS, due to the tidal resuspension of bottom sediments which contained large amounts of chlorophyll pigments (Tanaka *et al.*, 1982). Over 100mg $\cdot L^{-1}$ of SS was commonly

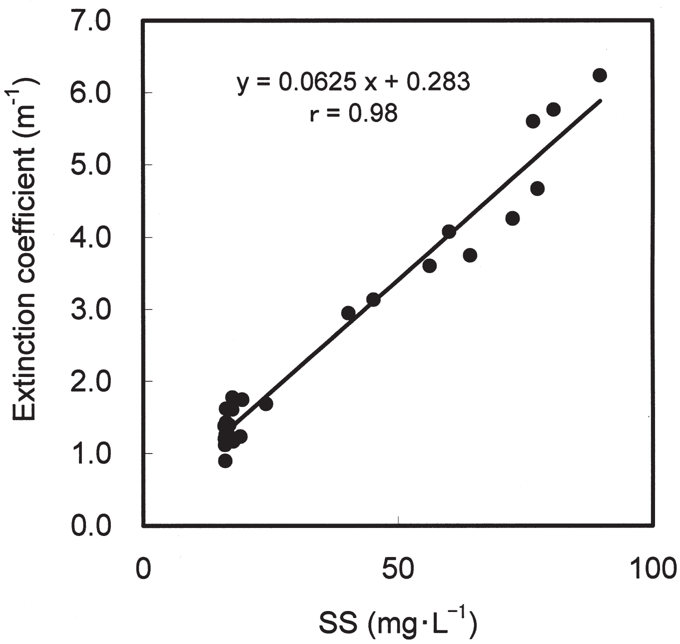

Fig. 2. Linear regression of extinction coefficient (k) against SS concentration, for measurements made at T4 on Nov. 25, 2003.

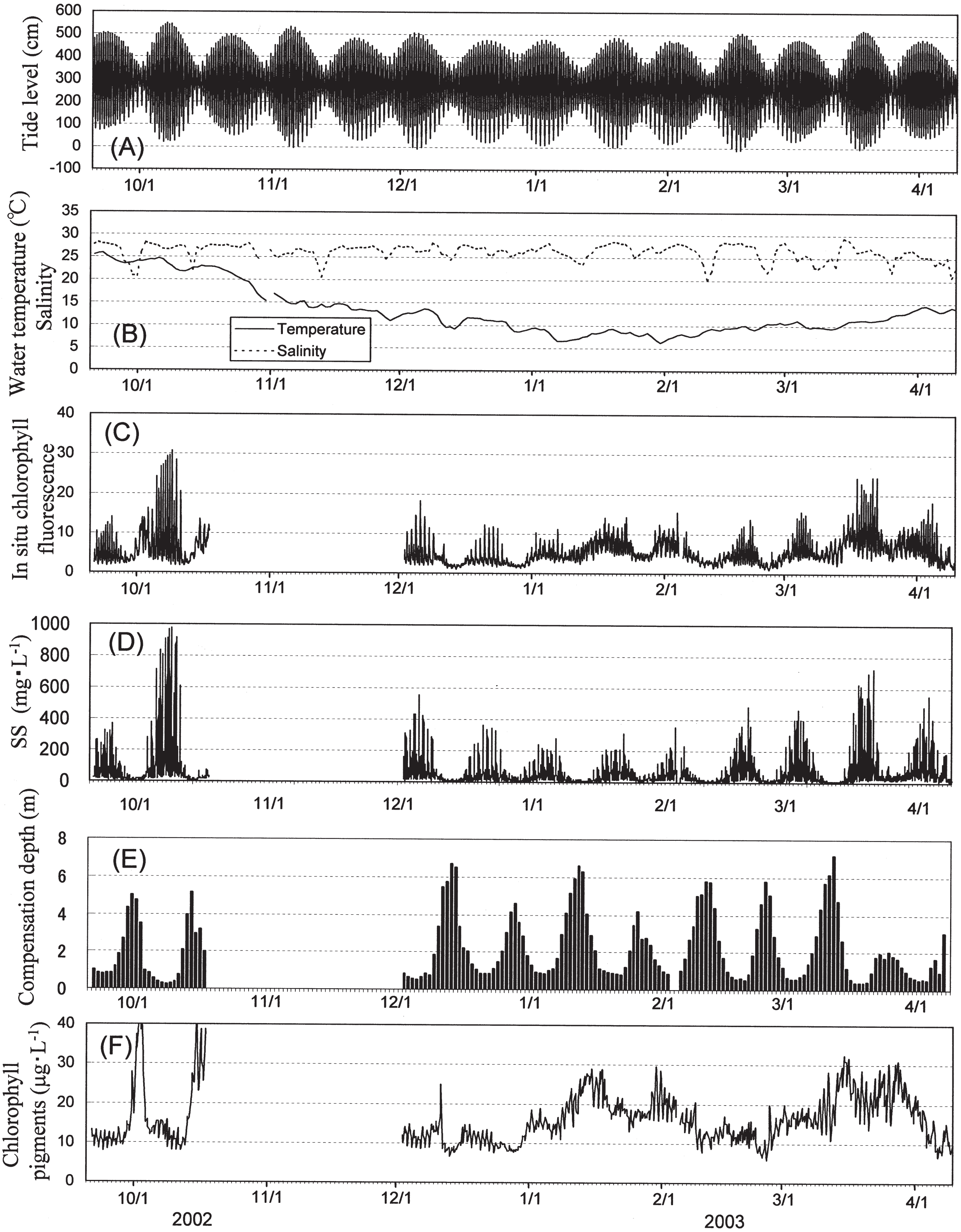

Fig. 3. Variations in tidal level at Miike (A), daily mean salinity and temperature (B), *in situ* fluorescence (C), SS (D), daily average compensation depth (E) and chlorophyll pigments at high water (F) at T4 (1m). SS, chlorophyll pigments and compensation depth were estimated from turbidity and *in situ* fluorescence.

observed in the inner Ariake Bay during spring tide which is equivalent to compensation depth lower than 0.7m. On the other hand, compensation depth was higher during neap tides, and occasionally reached to 6 m during the high season of Nori farming (late October to March).

As variations of in situ chlorophyll fluorescence include the influence of chlorophyll pigments in the resuspended sediments, especially at low water during spring tides, it is difficult to identify variation of phytoplankton biomass itself from Fig. 3(C). Therefore, in order to minimize the influence of chlorophyll pigments in the resuspended sediments, chlorophyll pigments data only at high water were plotted in Fig. 3(F). Phytoplankton biomass increased from neap tides to before spring tides, and decreased or stable during spring tides. During neap tides, lower salinity was observed (Fig. 3 (B)). These results indicate that the phytoplankton biomass increase from neap to before spring tides was caused by the higher nutrient availability in the surface low salinity water by the stratification and higher light availability with low turbidity. Significant increase of chlorophyll pigments (up to $30\mu g \cdot L^{-1}$) were observed in the middle of January and March, when compensation depth reached to 6m. Blooms of diatom species (*Skeletonema costatum*, *Chaetoceros* spp., *Thalassiosira* spp. in Jan., *Rhizosolenia setigera* in Mar., respectively) were recorded in those periods. While, during spring tides, phytoplankton bloom may be suppressed by low light availability with turbid water, strong mixing with offshore water and possibly mutual flocculation of phytoplankton together with resuspended sediments (Avnimelech *et al*., 1982).

During high season of Nori farming (from middle of December to March), SS was lower compared with other periods (from October to November and from end of March). Fig. 4 shows the relationship between tidal range at Miike and daily average SS at T4. Daily average SS increases exponentially with the tidal range, however, increasing rate during high season of Nori farming was lower in comparison with other periods. These results suggest that tidal current was reduced and resuspension of sediments was suppressed by the Nori farming gears.

The gradual reduction of tidal amplitude in recent

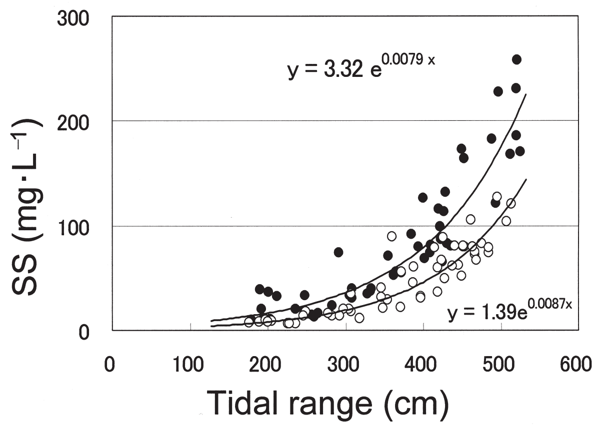

Fig. 4. Relationship between tidal range at Miike and daily average SS at T4.
○ : during high season of the Nori farming,
● : before and after the season of the Nori farming.

years is reported to approximately 4% (Takigawa and Tabuchi, 2002; Unoki, 2003), which is equivalent to the SS decrease of 11% on average and 17% on maximum, using the equations of Fig. 4. These observations indicate that the recent reduction of tidal currents is one of the contributing factors to the decrease of resuspension of the bottom sediments. Therefore, the resuspended sediment is considered to have key roles linking currents and phytoplankton production through light availability.

Hypoxia and resuspended sediments

Fig. 5 shows variations in the tidal level at T3, DO and SS at T1-T4 in the bottom water (0.5m above the bottom) during summer (9, July-3 Sept., 2003). The data of 6-10, Aug. and DO data at T4 (25, July-10, Aug.) could not be obtained by the instrument trouble or typhoon. At all stations, the high SS concentrations in spring tides decreased to below $10mg \cdot L^{-1}$ during neap tide. As the SS concentrations decreased during the neap tides, DO also decreased. At the north-western part of inner Ariake Bay, T1 and T2, DO decreased drastically to almost $0mg \cdot L^{-1}$ in late August. Mutual flocculation of phytoplankton and resuspended sediments leads to the removal of phytoplankton cells from the water column and their accumulation at the bottom (Avnimelech *et al*., 1982). The coincidence of drastic decrease of DO and SS during the neap tides indicates that the rapid decomposition

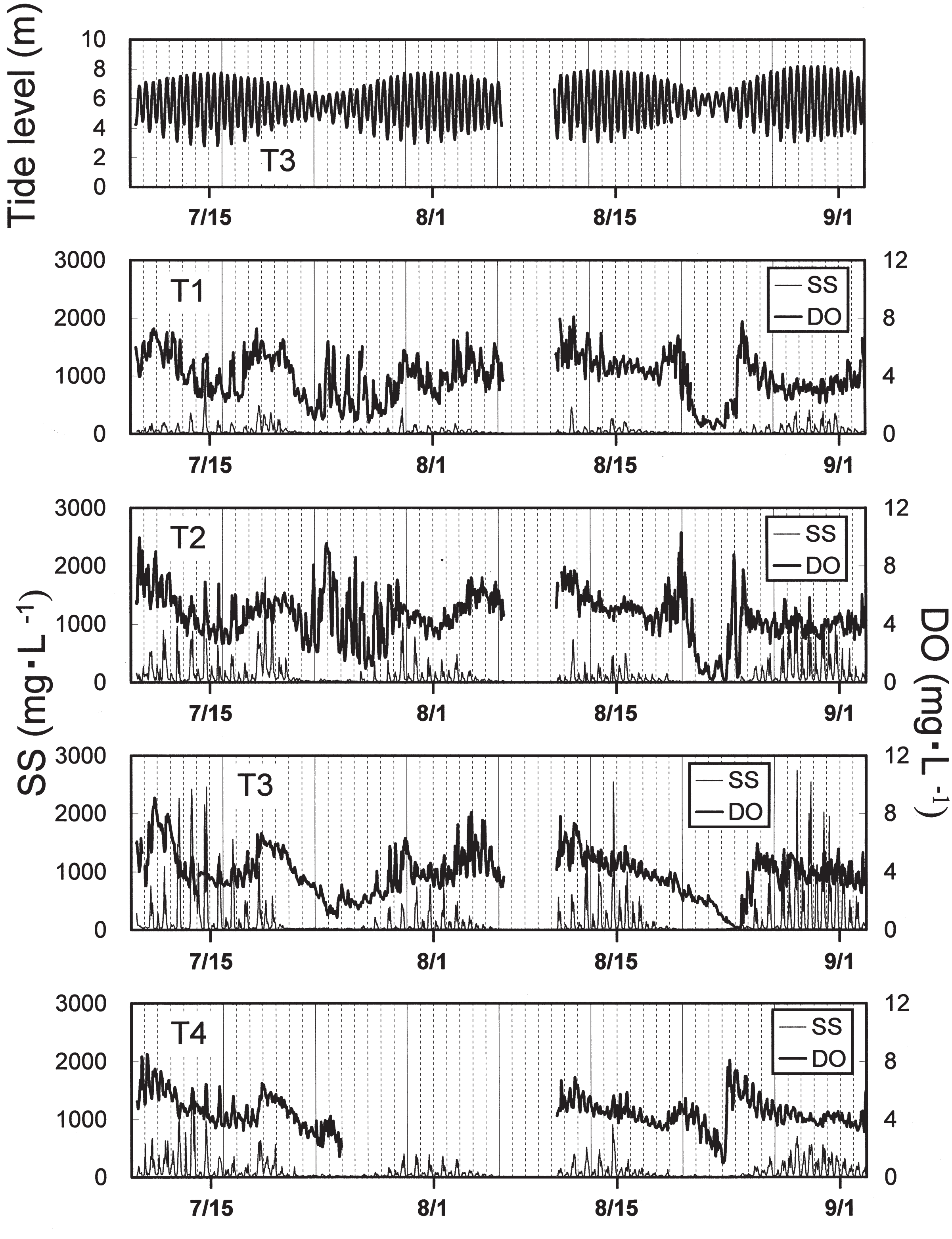

Fig. 5. Variations in SS, DO (B-0.5m) at T1-T4 and tide level at T3 during summer 2003.

of phytoplankton cells is taking place after the sedimentation.

Conclusion

The phytoplankton biomass increase from neap to before spring tides was caused by the higher nutrient availability in the surface low salinity water by the stratification and the higher transparency with low turbidity. While, during the spring tides, the increase of phytoplankton biomass was restricted by the low light availability with turbid water by the resuspended sediments, strong mixing with offshore water and possibly mutual flocculation of phytoplankton with resuspended sediments. In the Inner Part of Ariake Bay, tidal currents have become slower resulted from gradual reduction of tidal range and mean sea level rising, which weakened resuspension of bottom sediments and increased transparency and light availability for phytoplankton. Red tide phytoplankton cells and resuspended sediments accumulate on the bottom by the mutual flocculation during neap tides. Therefore, the drastic decrease of DO during the neap tides indicates the rapid decomposition of phytoplankton cells is taking place after the sedimentation. These observations indicate that reduction of tidal currents is one of the contributing factors to the changes of ecosystem in Ariake Bay, such as the frequent occurrence of red tide and hypoxia.

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Observation on behavior of the large suspension feeding bivalve *Atrina pectinata lisckeana* under natural conditions

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Abstract To evaluate an effect of environmental changes on the pen shell *Atrina pectinata lisckeana*, we conducted research on the valve movement of the pen shell; an indicator of their activity. We developed two types of data logger to measure the valve movement of the pen shells under field conditions. One is a wire-communication type for regions close to the shore while the other is an underwater type for offshore regions. The measurements were performed in a tidal flat and in a subtidal station in Ariake bay in 2004. The measurement in tidal flat revealed a distinct emersion effect, where the pen shells were closing their valves and remaining motionless during the emersion. This type of motionless period did not, however, occur when they were submerged. Measurement in the subtidal station revealed post-transplantation burrowing behavior and unusual single close-open actions during a storm.

Key words: Pen shell, *Atrina pectinata lisckeana*, valve movement, data logger

The pen shell *Atrina pectinata* is a large suspension feeding bivalve and one of the most important species in shell fisheries in Ariake bay Japan. The pen shell is also an important species in terms of its ability to construct benthic fauna. Their filtration and bio-deposition may affect the composition of the benthic fauna and environmental conditions (Cummings *et. al*., 1998; Norkko *et. al*., 2001). Therefore, the pen shell is important as a key species in the benthic community in Ariake bay. However, the pen shell production in Ariake bay has been decreasing since the 1960's. In a recent survey, mass mortality of the pen shells was observed in the fishing grounds (Matsui, 2002, Kawahara and Ito, 2003). Certain factors such as the development of a hypoxic water mass (Matsui, 2002), an increase of the muddy bottom area (Ito, 2004), and predation (Kawahara *et. al*. 2004) have been blamed for its decline. Despite intensive research, the mechanism for the decrease in the pen shell resources remains unclear. In previous studies, the gill activity of the pen shell related to the dissolved oxygen concentration (Yamamoto *et. al*. 1993) and the lethal level of dissolved oxygen (Akimoto *et. al*. 2004) were reported. However, the description of the pen shell activity under natural fishing ground conditions has yet to be produced.

The activity of bivalves has been also studied by measuring valve movement for mussels (Ameyaw-Akumfi 1987, Fujii and Toda 1991), scallops (Fujii and Sugiyama 1991), and short-neck clams (Fujii 1977, Fujii 1979). Most of these studies focused on the rhythmic activity of bivalves but Tyurin demonstrated that the valve movement of scallop and mussel can be a possible bio-monitor for unfavorable environments (Tyurin 1990). He reported that the frequency of valve movement was increased under low oxygen condition in Scallop. We found the valve movement of the pen shell also increases under hypoxic condition by laboratory experiment (Suzuki, unpublished data). Therefore, if the valve movement of the pen shell is monitored *in situ*, it is expected to contribute for understanding the mechanisms of the decrease of the pen shell. In

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the present study, the valve movements of the pen shells under natural conditions were measured and the resulting data revealed typical patterns which are discussed in relation to environmental conditions, as are the devices we developed.

Materials and Methods

The experiment was carried out at the west part of Ariake bay in Kyushu, Japan. One station was situated in the mud flat near Konagai, and the other in the subtidal area off Ohura (Fig. 1). The measurement period was from May 19 to June 30 in the mud flats and from August 24 to September 8 in the subtidal station in 2004, respectively. Pen shells were found to occur naturally in the vicinity of both experimental sites. The station in the mud flats emerged when the tide level went below 60cm in Takesaki. The expected tide level at Takesaki was available from the URL of the Japan Coast Guard. The depth at the subtidal station, meanwhile, was ca. 11m in mean low water level.

The pen shells used were collected from mud flats off Yanagawa about two weeks before the experiment. They were identified as *Atrina pectinata lisckeana*, based on the shell squamation (Yokogawa 1996). The shells were then kept in holding tank without being fed. Eight shells (138-190mm in SL) were used for the experiment. Shells were fitted with a sensor on one side of the valve and a magnet fitted on the opposite side by a plastic clip or cyanoacrylate instant glue. A hall element (THS130, Toshiba Semiconductor Co., Tokyo, Japan) and a magnet (Wilson *et. al*., 2002) was used as sensors for measuring the valve movement. The sensors were molded by Epoxy resin and were connected to

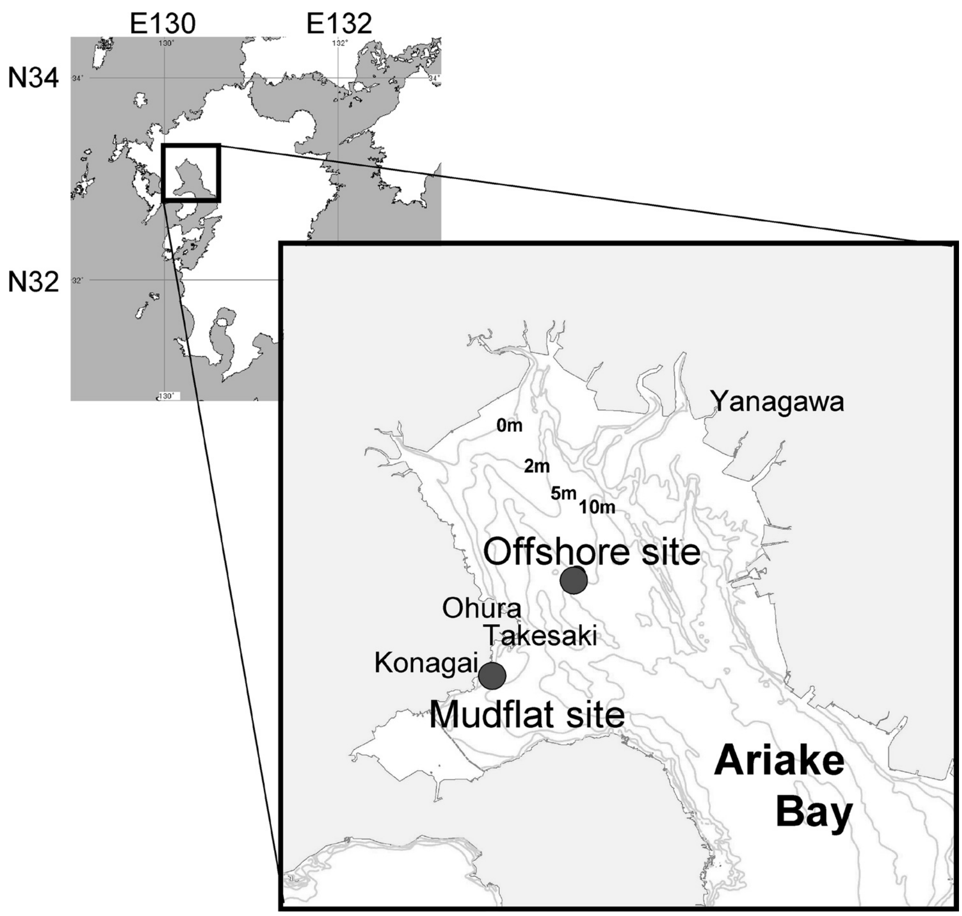

Fig. 1. The map of the study sites.

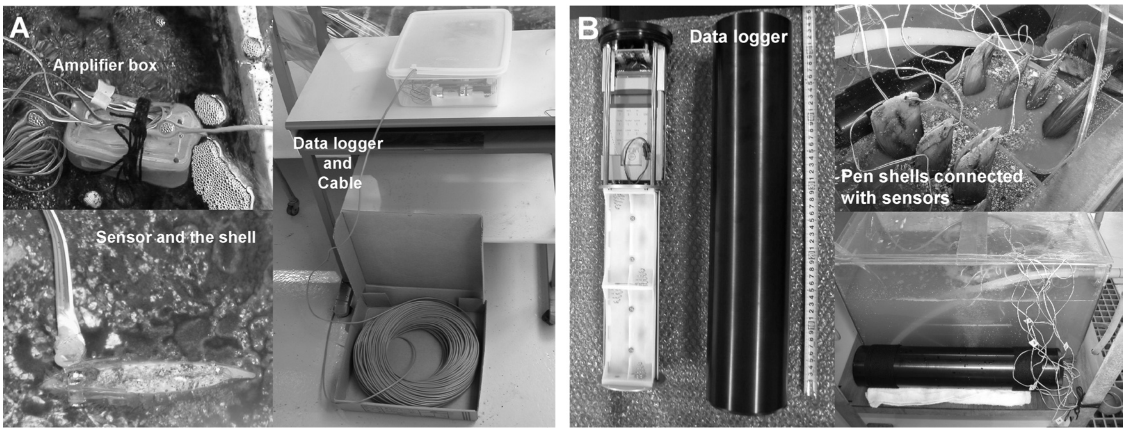

Fig. 2. The wire communication type data logger (A) and the under water type data logger (B).

the amplifier by 1m flat cables. The amplifier circuit, meanwhile, was built based on a gauss meter circuit (Shimada, 2003). When the shell closed their valves, the distance between the hall element and the magnet shortened, causing the output voltage of the hall element to rise.

Two types of data loggers were developed to measure the valve movement of the pen shell. One was of the wire communication type while the other was an underwater type (Fig. 2 (A), (B)). The wire communication type data logger was used for measuring in the mud flat while the underwater type was used in the subtidal station.

The amplifier circuit was molded by Epoxy resin to render it waterproof for the wire communication type. The signal from the amplifier circuit was transmitted to a data storage device using a multi wire cable. The data storage device (LAB-MIC 2A, ROHRM RIKEN. Co. Ltd, Shizuoka, Japan) used for the wire communication type data logger included 32 megabits of flash memory, with a recording period of about 10 days for two channels at intervals of 0.5 seconds.

The underwater model was assembled by Little Leonard Co. Ltd., Tokyo, Japan. The amplifier circuit and data storage device were built in a waterproof casing on the underwater type data logger. The casing was a cylindrical shape (10cm in diameter, 60cm in length) with 8 waterproof sockets used to connect the sensor cables. The data storage device (UL81, Unipulse Co., Tokyo, Japan) used for the underwater type data logger included 512 megabits of flash memory, with a recording period of about two weeks for 8 channels at one second intervals.

Results and Discussion

The measurements in the mud flats were carried out from May 19 to June 30. Unfortunately, the available data was recorded only for the first week because of the transfer cable being damaged by drift wood. The valve movement records of two individuals and the expected tide level at Takesaki are shown in Fig. 3. Two shells opened their valves for most of the recorded period. They also had frequent short term valve closures. The valve movement pattern showed both single and multiple close-open actions. The former is characterized by a close-open action occurring over an interval of more than a few minutes and the latter is characterized by a series of close-open actions repeated at intervals of less than 30 seconds. Our preliminary observation in the aquarium showed that the single close-open action occurred during the vomiting behavior to expel the sand from within the shell. This observation also showed that the multiple close-open action was apparent during burrowing behavior (Suzuki, unpublished data). The valve movement recorded in the mud flats demonstrated that the pen shells remained still, closing their valves during the emersion and they experienced burrowing behavior after they were submerged.

The measurements at the subtidal station were carried out from August 24 to September 8, with

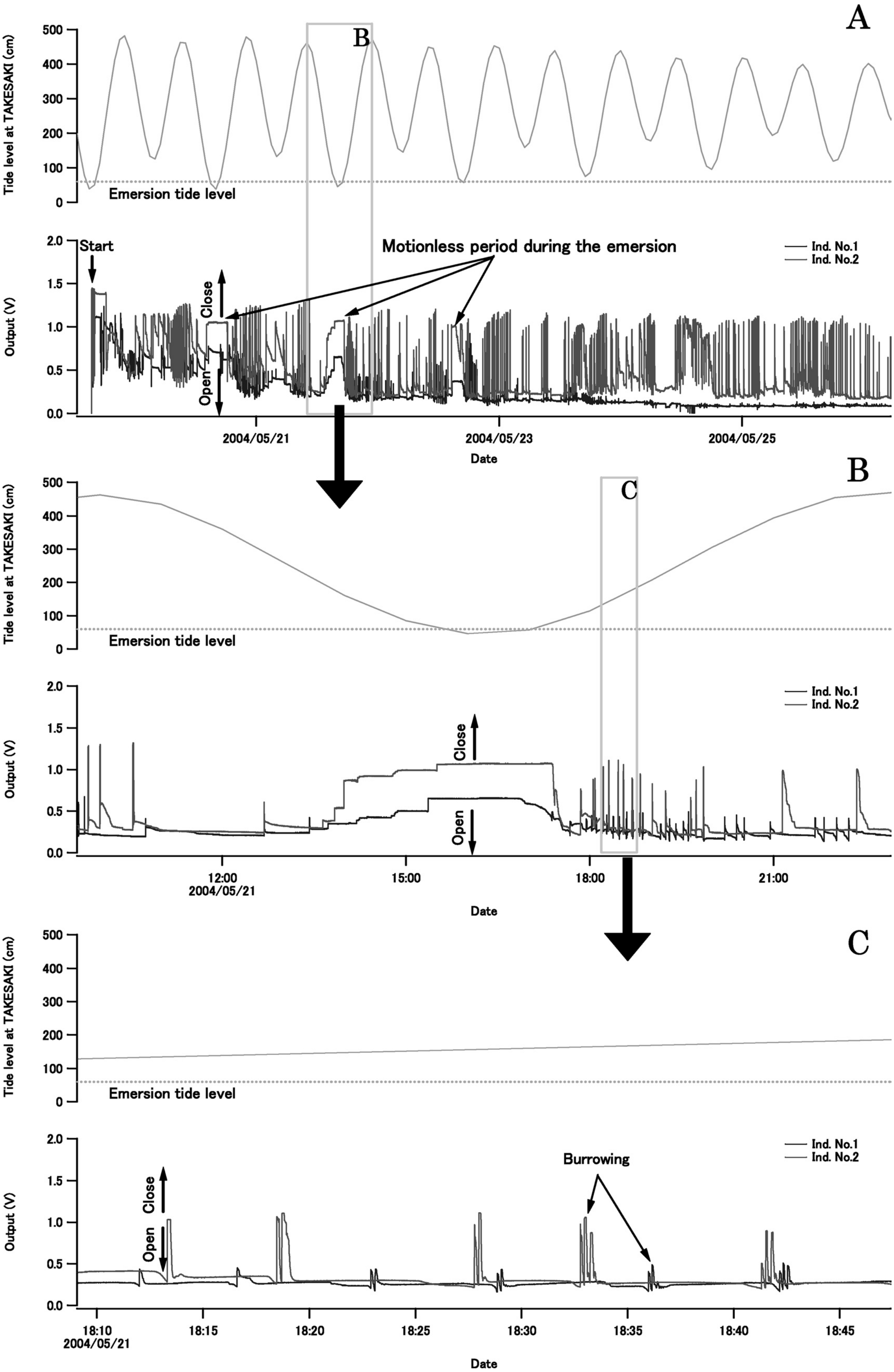

Fig. 3. (A) One week recordings obtained for valve movement of two pen shells on the mud flat. (B) Motionless period during the emersion and (C) multiple close-open action (burrowing) followed the motionless period.

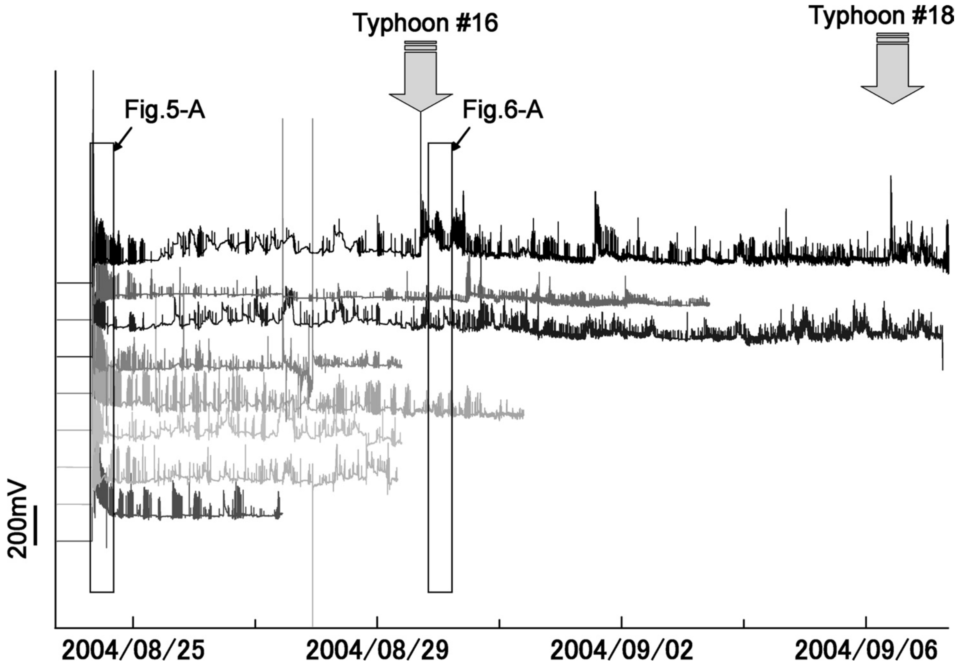

Fig. 4. The recordings obtained for valve movement of eight pen shells at subtidal station.

the records are shown in Fig. 4. Unfortunately there were two typhoons during this period and five shells were lost. Valve movement was most frequent just after the shells were transplanted and also frequently occurred following the encounter of the typhoon #16. By examining the details of the record, we found that the shells experienced multiple close-open actions just after being transplanted (Figs. 5A, B). So the pen shells are considered to have burrowed extensively after being transplanted to fix themselves in position. On the contrary, most of the valve movements during the encounter of the typhoon #16 were single close-open actions (Figs. 6A, B). This type of valve movement is similar to that of vomiting behavior, meaning these actions were thought to be a reaction of the pen shells to high turbidity or since they were covered with sand from heavy waves.

In the present study, the valve movement records assess the change in activity or behavior of the pen shells. This method could also be used to monitor the state of the pen shells within natural fishing grounds. To clarify the effects of environmental conditions such as oxygen deficient water on the pen shells, the activity of the pen shells and prevailing environmental conditions must be monitored at the same time. Further studies under laboratory condition are also required to understand the meanings and causes of change in the patterns of valve movement.

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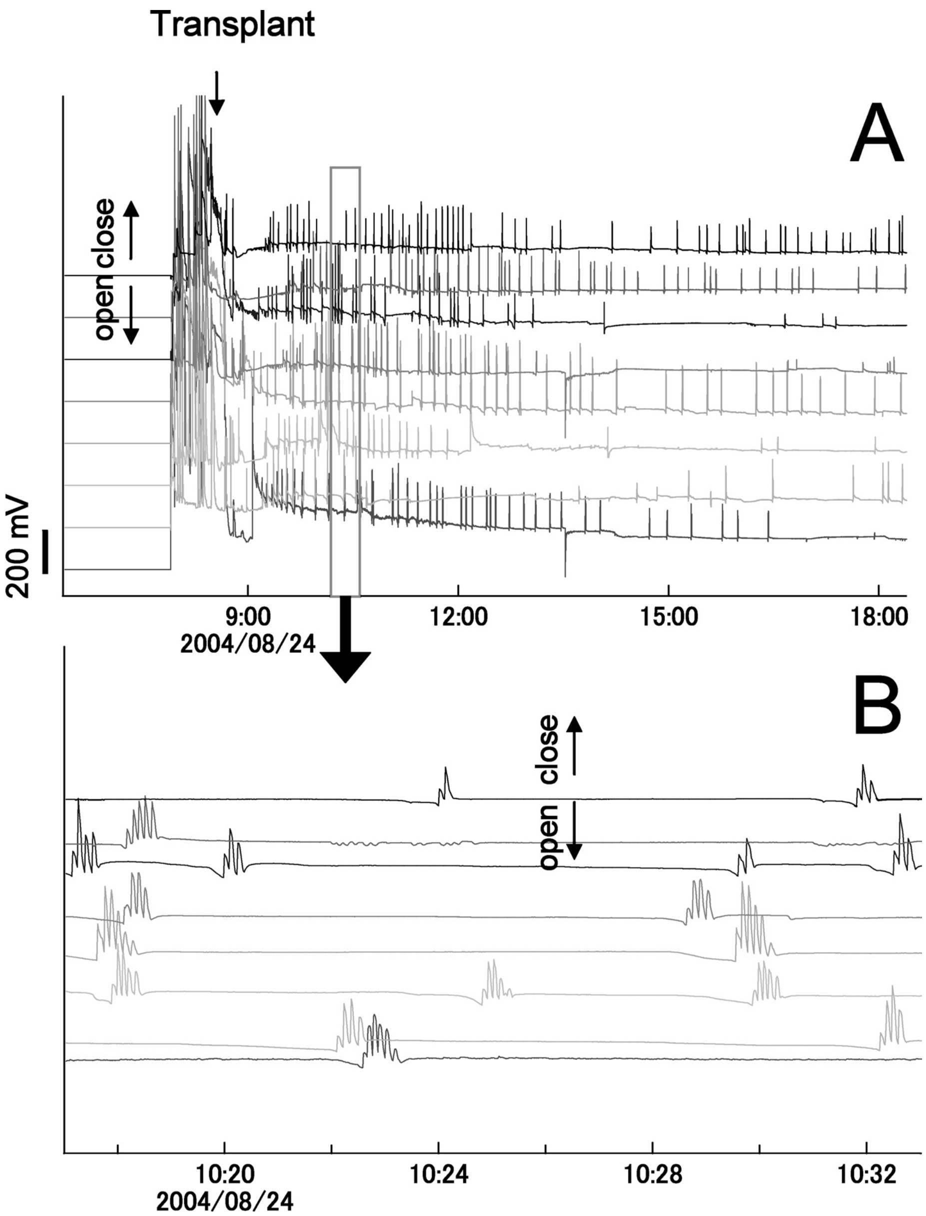

Fig. 5. (A) The recordings obtained for multiple close-open actions appeared just after pen shells were transplanted. (B) A 16-miutes portion of the record. Close-open actions were repeated within a minute.

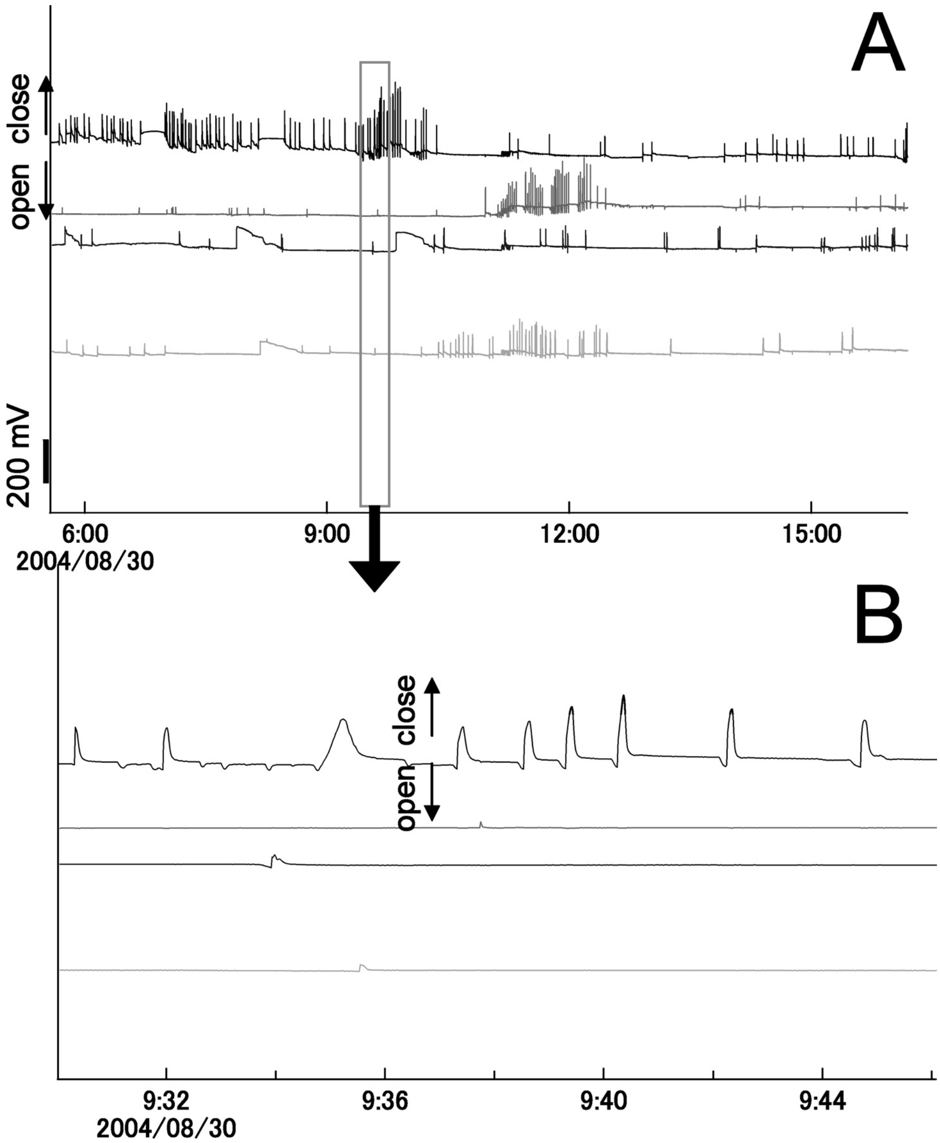

Fig. 6. (A) The recordings obtained for single close-open actions appeared during a storm. (B) A 16-miutes portion of the record. Close-open actions were repeated at least one or more minutes interval.

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和文要旨

環境変化がタイラギの活動に与える影響を把握するため殻体運動を測定する装置を開発し，小長井地先の干潟と大浦沖の潮下帯でタイラギの殻体運動を測定した。干潟上のタイラギは，干出時に殻を閉じて静止しており，潮が満ちると殻体運動が増加した。潮下帯の

タイラギでは移植直後の潜砂行動に伴う連続した殻体運動が記録され, その後殻体運動の頻度は減少したが, 台風の接近以降に潜砂行動とは異なる単独の殻体運動が増加した。

水研センター研報，第19号，27－32，平成19年
Bull. Fish. Res. Agen. No. 19, 27-32, 2007

Appropriate release number of juvenile red spotted grouper, *Epinephelus akaara*, into nursery reef and fishing port habitats

Shigenobu OKUMURA *

Abstract Six nursery reefs of ca. 20m^3 were installed off Shiraishi Island, central Seto Inland Sea, Japan in July 2000. Juvenile red spotted grouper were released into the reefs on October 2001. The densities of released juveniles were arranged at three levels, 500, 1,000 and 2,000 fish per reef. Part of the reef was salvaged from each reef three times to estimate the number of residual fish. The numbers of residual fish were directly proportional to the numbers of released fish until one month after release; however they were nearly even among the three levels at four months after release. Retention rates were inversely proportional to the released number. Release experiments into a fishing port were carried out in Ishima West Port located in central Seto Inland Sea, Japan. A total number of 15,000 and 1,500 juveniles were released into the port on October 1998 and November 1999, respectively. Respective recapture operation took place 16 and 28 days after the release using 16 and 20 fishing traps in the port. CPUE were 0.38 and 0.05 directly proportional to the number of released juveniles.

Key words: red spotted grouper, release experiment, stock enhancement, nursery reef, fishing port

Introduction

The red spotted grouper is a temperate grouper which is distributed from Southeast Asia to Far East. It has a high market price and seems to be a prominent species for stock enhancement because of its non-migratory habitat and relatively small stock size. Stocking efficiency was obvious when 1+ year old fish were released into natural conditions; however 0+ year old fish release had little efficiency in this species (Okumura *et al*., 2002). It was a large problem that how to care the released 0+ year fish and nurse them to 1+ year old. One of the solutions of this problem is caring the juveniles by using artificial nursery reef or fishing port. In this paper, three release experiments were introduced and discussed on the carrying capacity of the nursery reefs and fishing port.

Release experiment into nursery reefs

Materials and Methods

Prior to this experiment, materials and structure of the nursery reef were designed in the laboratory (Okumura *et al*., 2002) and under natural conditions (Okumura *et al*., 2003a). Fig. 1. shows schematic diagram of the nursery reef. The nursery reefs consisted of a 3.6 m square concrete base, 4 iron poles of 1.6 m tall, and a top panel. Top panel was filled up with oyster shells (250 kg/m^3) to enhance the food organisms for released fish. Each nursery reef had 6 test units of 75 cm cube. Test unit was consisted of iron frame and 25 mesh pipes, 15 cm in diameter and 75 cm long. Each pipe had a string of scallop shells in it. The mesh size of the pipe and space between the shells were planed to match with the released fish size. These test units

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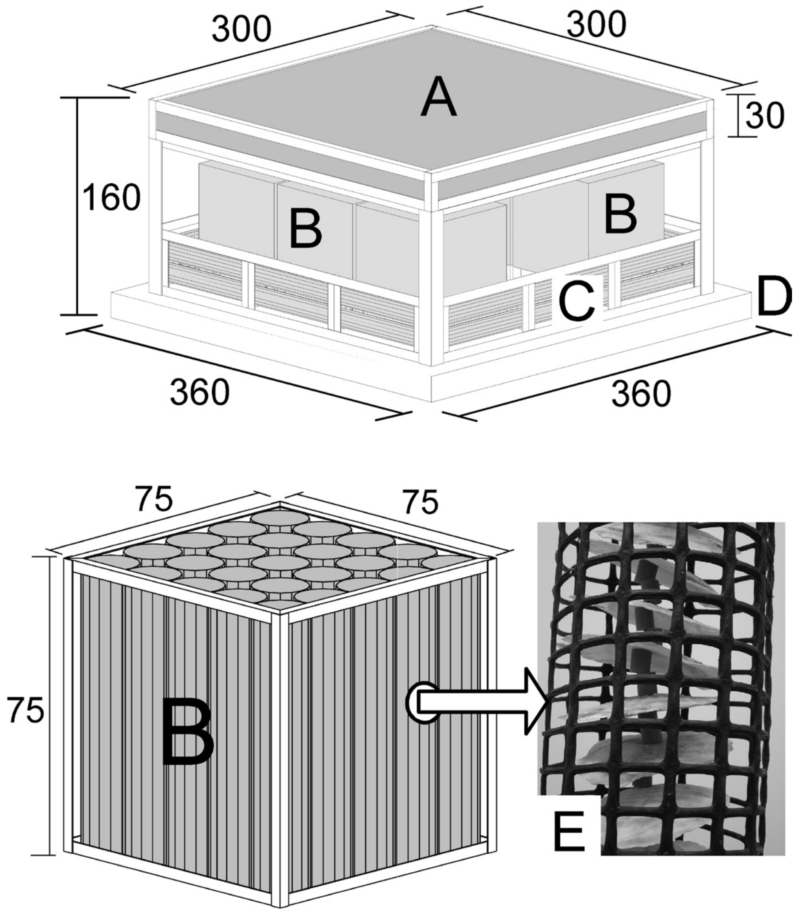

Fig. 1. Structure of the nursery reef.
A, top panel; B, test unit; C, side panel; D, concrete base; E, mesh pipe filled with string of scallop shells. Values are in cm.

were detachable from the nursery reef in order to estimate the number or conditions of the residual fish by salvage operation. Side panel was attached to prevent the fish escaped from the reef and/or propagate the food organisms. Six nursery reefs were built and installed on the bottom (5-6 m in water depth) off Shiraishi Island, central Seto Inland Sea, Japan (Fig. 2., 3.) in July 2000. Artificially reared red spotted grouper juveniles (67.6 ± 7.0 mm in total length) were released into the reefs on 16 October 2001. All fish were marked by clipping the left or right ventral fin. The fish were packed in a basket and divers delivered the basket into the reef and opened it in each reef. The densities of released juveniles were arranged at three levels, 500 fish per reef, 1,000 fish per reef and 2,000 per reef, and each density level tested at 2 reefs. Underwater observation took place five times, 7, 27, 56, 92, and 119 days after release to count the number of residual fish in the reefs. A test unit was salvaged from each nursery reef three times, 7, 27, and 128 days after release, to estimate the number of residual fish. Salvaged test units were took apart on the boat and each number of the recaptured fish was counted. After the operation, the test units were rebuilt and returned to the original reef. Recaptured fish were also re-released into their own reef.

Results and Discussion

Each number of fish in the reefs observed underwater is shown in Fig. 4. At first operation

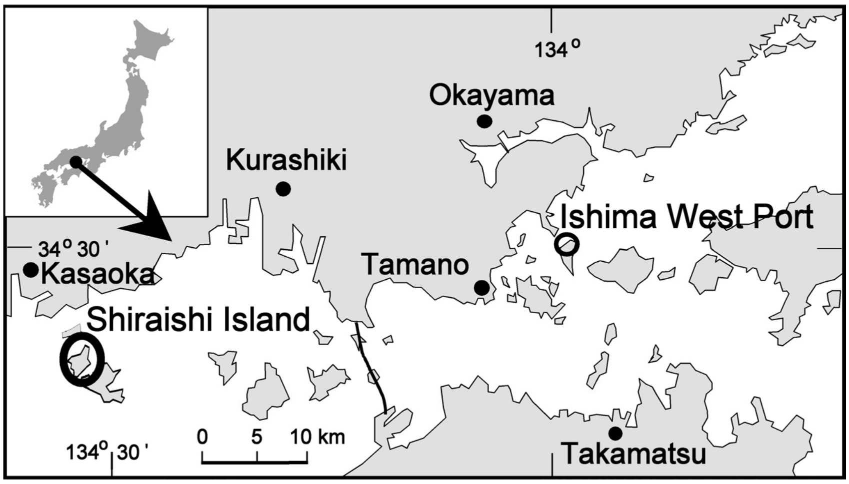

Fig. 2. Location of the experimental area.

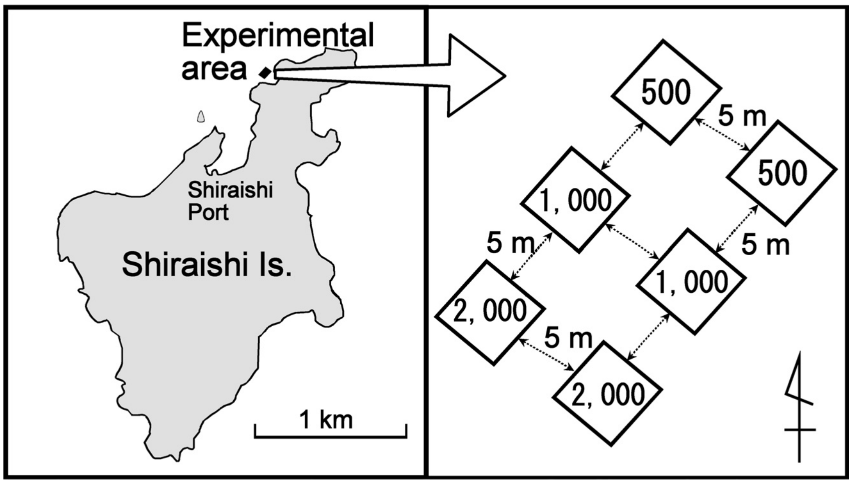

Fig. 3. Experimental area, nursery reefs arrangement, and release number of juveniles into each reef.

the numbers of observed fish were parallel to the released density. From the second observation, the observed numbers of fish in 2,000 fish per reef group decreased and were close to 1,000 fish per reef group. At 92 days after release, numbers of fish decreased to 4-10 per reef and were close to each other. At the final observation the observed numbers were almost even and partly reversed like 8 fish in 500 fish per reef group versus 0 in 1,000 fish group. Fig. 5. shows the results of three salvage operation. The upper figure shows transition of the estimated number of fish per reef, number of recaptured fish multiplied 6 (number of test units in each reef). In this figure, tendency of the decrement was the same as Fig. 4. The lower figure of Fig. 5. shows transition of the retention rates which were calculated from estimated number of residual fish divided by numbers of released fish. The retention rates were almost inversely proportional to the released number through the experimental duration. These results indicate that releasing 2,000 fish per reef is effective to retain a large number of released fish in a reef for a month; and releasing 500 fish is efficient to obtain a high retention rate at four months after release. Thus the appropriate number of released fish should be determined depending on the duration spent in the nursery reef.

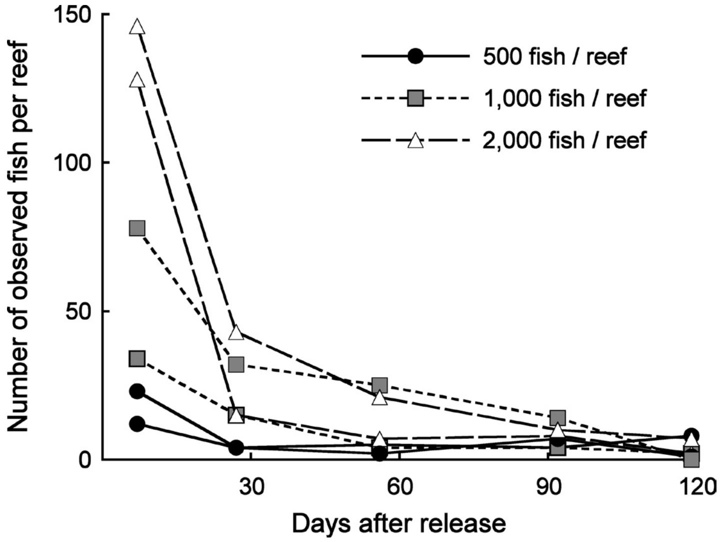

Fig. 4. Number of residual fish observed under water.

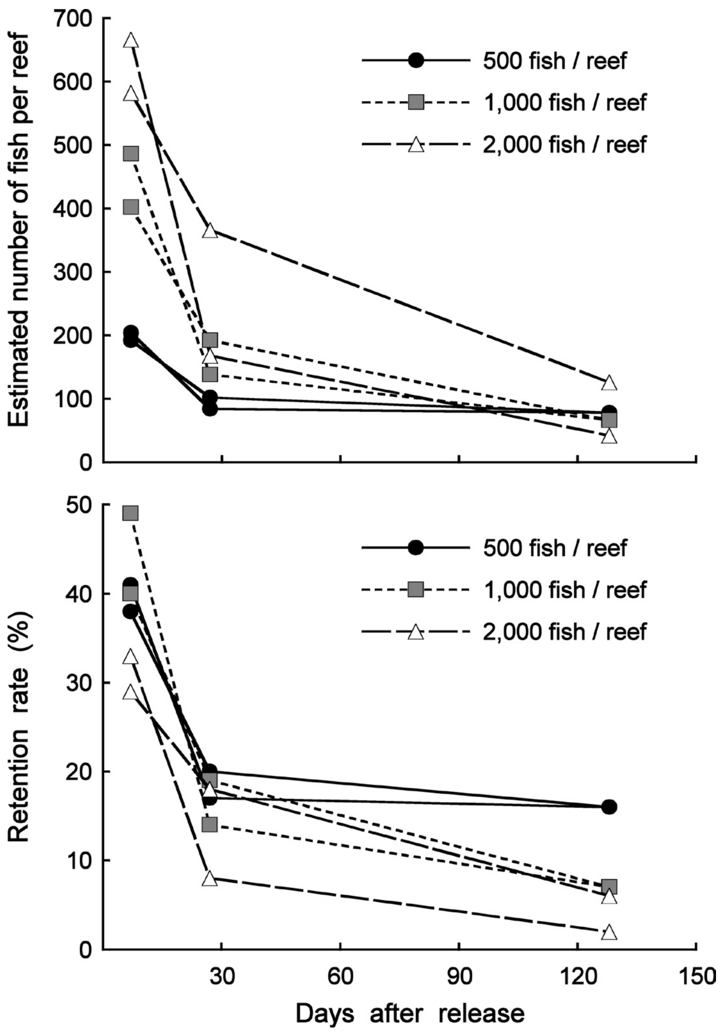

Fig. 5. Number of the residual fish and retention rate estimated from salvage operations.

Release experiment into fishing port

Materials and Methods

These experiments were carried out in Ishima West Port (Fig. 6.) which is shallow (2-4 m) and small (4500 m^2) port located in central Seto Inland Sea, Japan (Fig. 2.). The port had many crevices on its wall and bottom, since it was mainly built of rock arrangement. A total number of 15,000 artificially reared juveniles (69 mm, mean total length) were released into the port on 13 October 1998. Recapture operation took place 16 days after the release using 16 fishing traps (60 × 45 × 20 cm) in the port. All traps with bait fish were spaced evenly on the seabed in the port along a pier on noon 28 October. The traps were salvaged 24 h after setting and organisms in it were caught. A total number of 1,500 juveniles (109 mm) were released into the same port on 11 November 1999. Recapture operation was similarly conducted using 20 traps 28 days after the release.

Results and Discussion

Table 1. shows the results of these release experiments. Total number of recaptured fish in 1998 was 6 and catch per unit effort (CPUE) was calculated as 0.38 (6 fish per 16 traps). Only one fish was recaptured in 1999 and CPUE was 0.05 (1/20). Although these operations were experimental and the calculated figures were estimates, CPUE seemed to be directly proportional to the number of released juveniles. The retention rate may be fixed unrelated to the number of released fish within the limits of 1,500-15,000 fish per port. Further release experiment, less than 1,500 fish or more than 15,000 fish into the port, will be useful to estimate the carrying capacity of the port.

Acknowledgements

The nursery reef study was granted by Fishery

Fig. 6. Ishima West Port.

Table 1. Results of the recapture operations in Ishima West Port

Release		Recapture			
Date	No. of fish	Days after release	No. of fish	No. of traps	CPUE*
13 Oct. 1998	15,000	16	6	16	0.38
11 Nov. 1999	1,500	28	1	20	0.05

* No. of recaptured fish / No. of traps

Agency Japan to develop the nursery reef for stock enhancement from 1999 to 2001. The nursery reef study was collaborated with Okayama Prefecture Office Fisheries Division and Okayama Prefectural Fisheries Experimental Station. I thank members of the nursery reef development committee for their useful advice and suggestion. Thanks are also to the staff of Tamano Station of former JASFA for their assistance.

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An appropriate stocking size of juvenile Japanese flounder, *Paralichthys olivaceus*, in consideration of carrying capacity

Yoh YAMASHITA [*1] and Yutaka KURITA [*2]

Japanese flounder *Paralichthys olivaceus* is a major coastal commercial fish. The total catch of the flounder is stable between 6,500 and 8,400 tonnes in the last decade. It is also one of the major target species of stock enhancement in Japan. A total of 30 million juveniles are released every year. Economic return rate (amount of catch / cost of stocking) can increase to 2.5 in the case appropriate releasing techniques are applied. Stocking size is one of the most important techniques to be considered as well as the size at release and the timing of release. We applied an ecophysiology model to predict the growth of juvenile Japanese flounder and to evaluate an appropriate stocking size under the criterion that released fish, as a competitor of wild one for food, do not restrict the growth of wild fish. This model consists of 5 compartments (i. e. wild flounder, released flounder from hatchery as a competitor, other competitors, mysids as a main food item, predators) and includes various physiological responses to varying environments (mainly temperature) and ecological interactions (i. e. prey-predator relationship and competition for food) among these compartments. The predicted growth of both wild and released flounders until 65 days after stocking (9 November) well agreed with the observed ones at Ohno Bay, a small shallow sandy area up to 10m deep in the northwest of Japan. Wild flounder would reach to 141mm in TL on 9 November without any released flounder, while in fact they grew only to 109mm. The model explained that the standing biomass of mysids decreased because the amount of predation on mysids by both wild and released fish exceeded the production which was controlled by temperature and abundance of mysids themselves, and that led to the restricted growth of wild flounder. An appropriate stocking level below which release of hatchery-raised flounder would not retard the growth of wild one was predicted as 49,000 individuals while actual stoking level was 76,300.

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Impacts of oyster cultures on nitrogen budgets in Hiroshima Bay, the Seto Inland Sea of Japan

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Abstract The impact of oyster culture on the nitrogen budget was demonstrated for the northern Hiroshima Bay. The output from a simple two-layer box model and nitrogen measurements in the bay over a 1 year period were used to estimate the nitrogen budget in the northern Hiroshima Bay (NH). The annual dissolved inorganic nitrogen (DIN) budgets indicated that all input terms to the northern Hiroshima Bay were equivalent to 22±7.8 ton N d^{-1}, whereas DIN export to the central part of the bay was equivalent to 14±13 ton N d^{-1}. These results suggest that a significant part of DIN input is consumed by phytoplankton and converted into the particulate form in the NH region. Estimated filtration rates of cultured oysters (7.3 ton N d^{-1}) suggested that oyster cultures play a significant role for removing the particulate N from the water column in Hiroshima Bay. In addition, the amount of nitrogen harvested as oyster products was about 0.66 ton N d^{-1}, which is about 6% of daily terrestrial DIN input into the NH region. The removal rate through oyster harvesting is five times higher than that by fishing activities, suggesting that oyster culture plays a significant role on the recycling of nitrogen from Hiroshima Bay to the land.

Key words: environmental impacts, Hiroshima Bay, nitrogen budgets, oyster cultures

Bivalve aquaculture has some additional function other than food production, and can have a variety of effects on coastal and estuarine ecosystems. For example, bivalves filter suspended particle matter, both living and detrital, in the water column. It has been suggested that the grazing activity of bivalve populations controls phytoplankton dynamics on the scale of entire embayments (Cloern 1982). High rates of organic biodeposition near aquaculture sites have been shown to result in anaerobic benthic environments (e.g. Hatcher *et al.* 1994), and change the benthos community (e.g. Crawford *et al.* 2003). Harvesting activities can remove nutrients such as nitrogen and phosphorus from coastal and estuarine areas (e.g. Songsangjinda *et al.* 2000). As such, bivalve aquaculture can significantly alter material and energy flows in coastal and estuarine ecosystems.

Hiroshima Bay is located in the western part of the Seto Inland Sea of Japan, having a surface area of ca. 1,000km^2 and a mean depth of ca. 25m (Fig. 1). The annual oyster production in the bay is 15,000-30,000 tons, which accounts for about 60-70% of oyster production in Japan. A method of hanging oysters under a floating raft with a size of 20×10m has been used for oyster culture in the bay. A large number of floating rafts can lead us into a belief that oyster cultures have some impact on the ecosystem of Hiroshima Bay.

The objectives of this study were twofold. First, I wished to construct a nitrogen budget for Hiroshima Bay, based on the field observations and a simple box model analysis. My second objective was to examine filtering activity of phytoplankton particulate nitrogen by cultured oysters and removal efficiency of nitrogen from the bay by oyster harvesting. The results and discussions of this study will be elaborated in detail elsewhere, and briefly

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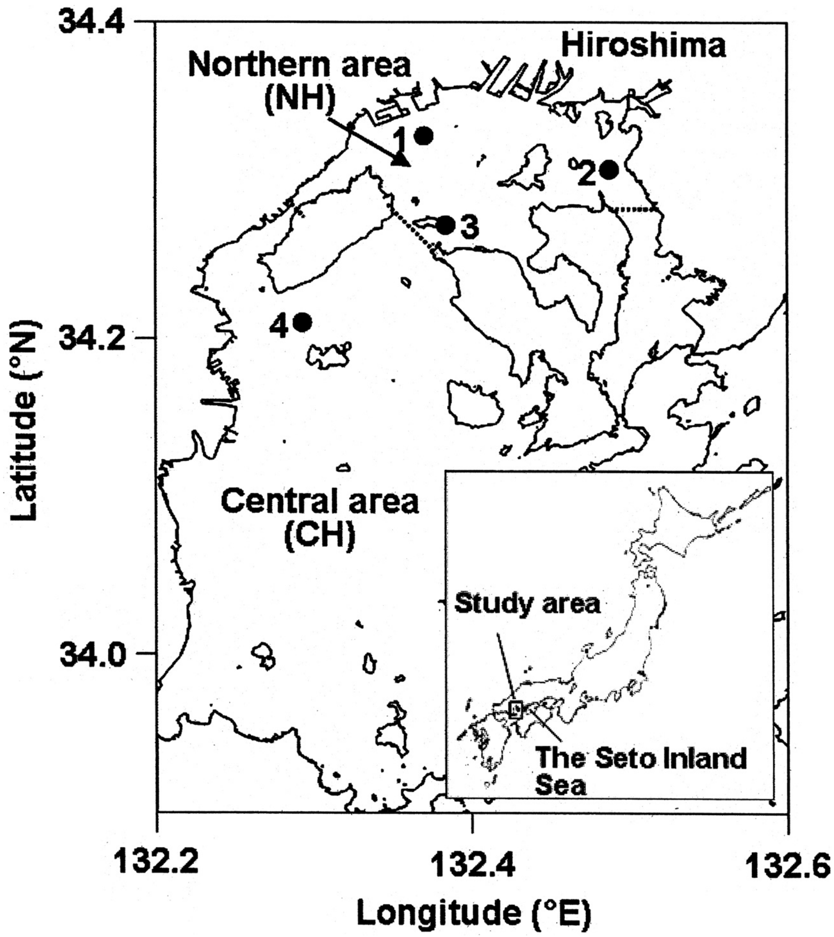

Fig. 1. Study area and sampling stations in Hiroshima Bay. Box dimensions for the model analysis are also given.

outlined here.

Nitrogen budgets in the northern part of Hiroshima Bay

A simple box model was used to characterize the residual circulation in the bay and then to estimate the nitrogen budgets in the northern part of Hiroshima Bay. Hiroshima Bay was divided into two adjacent boxes, northern Hiroshima Bay (NH) and central Hiroshima Bay (CH), depending on the hydrological characteristics (Fig. 1). On the basis of a two layered circulation pattern, each box was segmented into two layers separated by a zero-velocity level which was fixed at 5m depth (Fig. 2). Assuming that the volume of each box remains constant over time scales greater than 1 tidal cycle, the following relationships can be described for the budget of salinity in each box

$$Q_f + Q_{21} - Q_{13} = 0$$

$$V_1 \frac{dS_1}{dt} = S_2 Q_{21} + D_{12} (S_2 - S_1) - S_1 Q_{13}$$

$$Q_{42} - Q_{21} = 0$$

$$V_2 \frac{dS_2}{dt} = -S_2 Q_{21} + D_{12} (S_1 - S_2) - S_4 Q_{42}$$

where Q_f is the freshwater inflow, Q_{ij} is the transfer coefficient from Box-i to Box-j, D_{12} is the vertical mixing between Box-1 and Box-2, V_1 and V_2 are the volume of Box-1 and Box-2, respectively, and S_i are

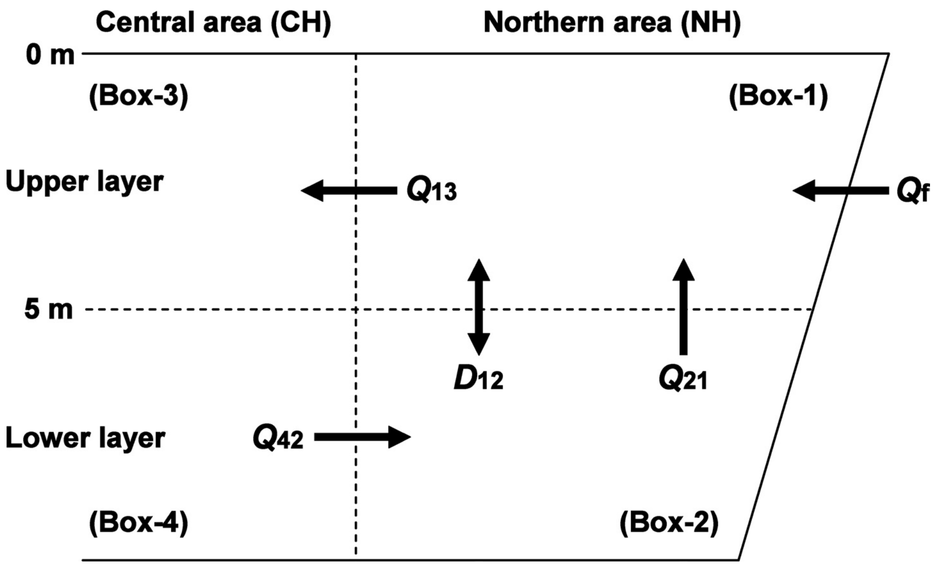

Fig. 2. Schematic diagram for the box model used in this study. Q_f, Q_{ij} and D_{12} represent the freshwater inflow, the transfer coefficient from Box-i to Box-j and the vertical mixing between Box-1 and Box-2, respectively.

the averaged salinity in Box-i. Q_f was calculated as the sum of the discharge from the Ohta River and sewage treatment plants, precipitation and evaporation. Dissolved inorganic nitrogen (DIN) fluxes in the NH region of Hiroshima Bay were estimated from the output of the box model combined with measurements of DIN in the river, the sewages and the bay.

Monthly measurements of water temperature, salinity and DIN concentration were made from Apr 2001 through March 2002 at 3 stations in NH region and one station in CH region (Fig. 1). The Ohta River discharge and DIN concentration in the river were obtained from the River Bureau, Ministry of Land, Infrastructure and Transport, Japan and the Hiroshima Prefecture Environmental Bureau, respectively. The sewage discharge and DIN concentration data were provided by the Hiroshima City Sewage Bureau. Rainfall data was obtained from the Hiroshima Meteorological Local Observatory. Evaporation was calculated from an empirical relationship based on wind velocity and vapor pressure.

During the stratified season (April to August), the Ohta River and sewage treatment plants supplied 4.2 ± 2.5 and 6.3 ± 1.3 ton N d^{-1} of DIN, respectively, to the NH region (Fig. 3A). DIN export to the CH region was 3.7 ± 1.3 ton N d^{-1}, significantly lower than a sum of DIN input from the river, sewage and the CH regions (5.2 ± 2.0 ton N d^{-1}). River and sewage DIN inputs to the NH region were 3.7 ± 1.7 and 6.4 ± 0.8 ton N d^{-1}, respectively, during the vertically mixed season (September to March), similar to those during the stratified season (Fig. 3B). On the other hand, DIN export to the CH region (22 ± 12 ton N d^{-1}) was significantly greater than that during the stratified season.

The average terrestrial DIN input during the study period was 10 ± 2.6 ton N d^{-1}. Based on the data during April 1996 to March 1997, Lee and Hoshika (2000) estimated the combined river and sewage DIN inputs to the NH region to be 327 ton N $month^{-1}$ (11 ton N d^{-1}) which was similar to the estimate made by the present study. The annual DIN budget (Fig. 3C) indicated that all input terms combined river, sewage and the CH region, to the NH region were equivalent to 22 ± 7.8 ton N d^{-1}. On the other hand, DIN export to the CH region was equivalent to 14 ± 13 ton N d^{-1}. These results suggest that a significant part of DIN input is consumed by phytoplankton and converted into the particulate form in the NH region, especially in

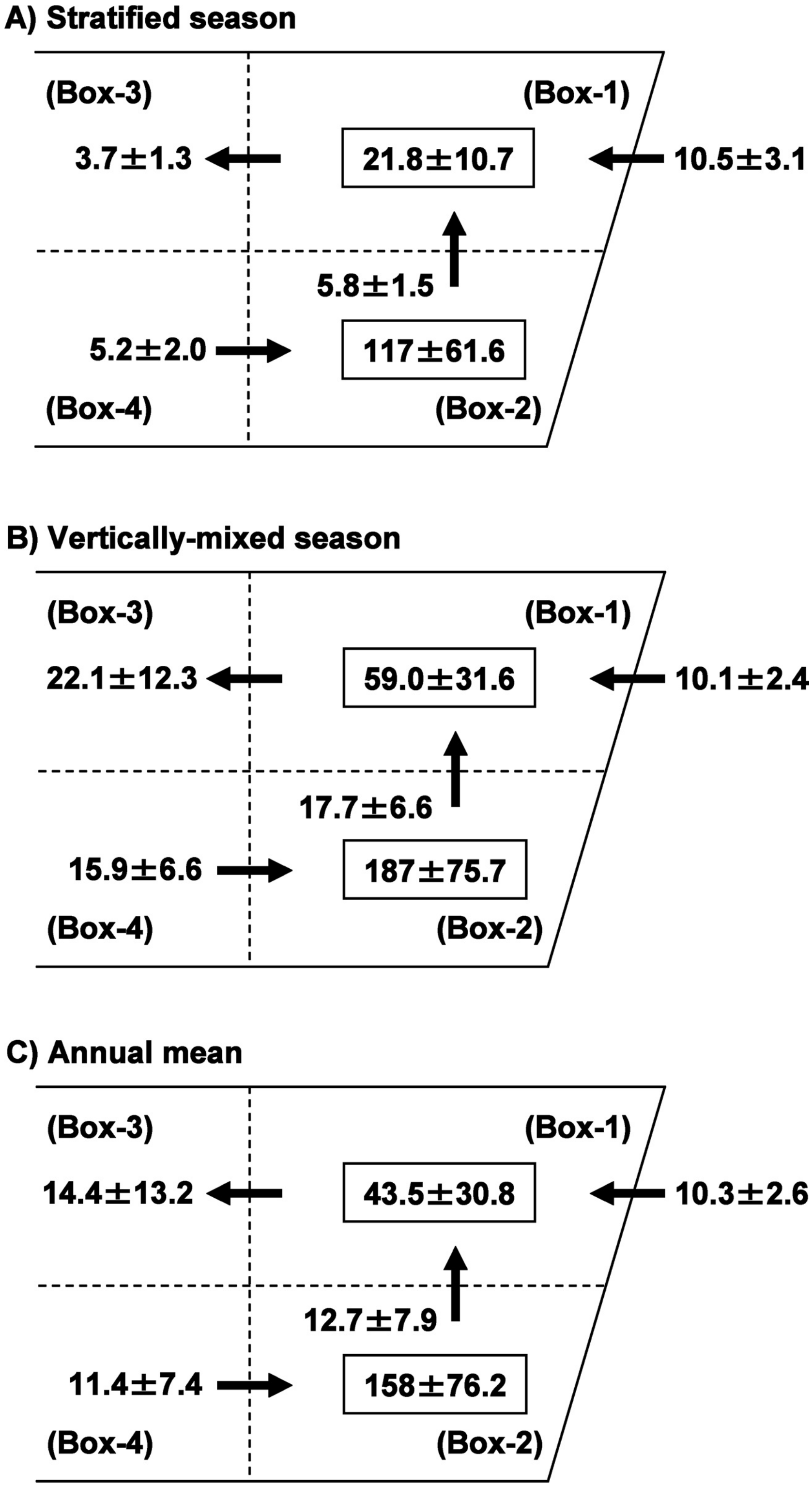

Fig. 3. DIN budget in the northern Hiroshima Bay. A) stratified season (April to August 2001), B) vertically mixed season (September 2001 to March 2002), and C) annual mean during April 2001 to March 2002. Arrows represent mean fluxes (±1 SE) in ton N d^{-1}. Values within square represent mean standing stocks (±1 SE) in ton N.

the upper layer. Phytoplankton productivity in the NH region of Hiroshima Bay was measured at the same time as nutrient samples were collected for this analysis. High phytoplankton nitrogen demand (228 mg N m^{-2} d^{-1}), which estimated from annual carbon productivity with the Redfield ratio (Redfield 1958), strongly supports the suggestion driven from the box model analysis.

Filtering activity of phytoplankton particulate nitrogen by oyster cultures

The grazing activity of oyster cultures was determined from the filtration rate and the ambient phytoplankton biomass. In the present study, oyster filtration rate was estimated as a function of total oyster biomass and water temperature (Chapelle et al. 2000). The monthly cultured oyster biomass was estimated by working backward from the harvest with first-order approximation for two year of cultivation period.

On an annual basis, Chl. *a* loss through oyster grazing was estimated to be 0.83 ton Chl. *a* d^{-1}, corresponding to be 7.3 ton N d^{-1} with a phytoplankton C: N ratio of 5.7 and a C: Chl. *a* ratio of 50: 1. This result suggests that an average 20% of the phytoplankton production (36 ton N d^{-1}) is consumed by cultured oysters in the NH region of Hiroshima Bay.

Micro- and macro-zooplankton are generally principle consumers for phytoplankton community. Extrapolating from the biomass data measured during the same study period in accordance with Uye et al. (1996) and Uye and Shimazu (1997), annual grazing rates of micro- and macro-zooplankton were estimated to be 2.4 and 4.0 ton N d^{-1}, respectively in the NH region (unpublished data). Therefore, oyster grazing accounts for 53% of daily phytoplankton nitrogen loss, suggesting that oyster cultures play a significant role for removing the particulate N from the water column in Hiroshima Bay.

Removal efficiency of nitrogen from Hiroshima Bay by oyster cultures

Annual oyster production in Hiroshima Bay was about 19,500 ton during April 2001 to March 2002. Given that the nitrogen content of cultured oyster was account for 1.24% of fresh meat wet weight production (Whyte and Englar 1982), the nitrogen removal rate through oyster harvesting was estimated to be 0.66 ton N d^{-1}. On an annual basis, this rate is account for 6.4% of daily terrestrial DIN input into the NH region. On the other hand, the nitrogen removal rate through fisheries was estimated to be 0.15 ton N d^{-1}, from annual catches of 5,030 ton with fish nitrogen composition of, indicating that oyster cultures recycled nitrogen to terrestrial areas in quantities approximately 5-fold greater than fisheries in Hiroshima Bay.

Conclusion

In summary, the present study has shown that oyster cultures have a significant impact on the nitrogen cycles in Hiroshima Bay in terms of removing the particulate matter and nitrogen from the water column. These results suggest that oyster cultures could be used as a possible tool for suppressing eutrophication in addition to their primary function of food production. However, large oyster populations can lead to a variety of negative effects on the benthic ecosystems. Therefore, appropriate management of oyster cultures is necessary for beneficially operating their removal efficiency of nitrogen.

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A framework for developing "ecological carrying capacity" mathematical models for bivalve mollusc aquaculture

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Abstract Aquacultural production of suspension-feeding bivalve molluscs can profit from information on the stocking density at which commercially valuable meat production is maximized. Predicting these stocking densities in the natural environment is difficult a priori because of the complex interacting effects of environmental variables on bivalve growth (e.g., food availability varies with rates of phytoplankton production, water currents affect "food flux" to the bivalves, etc.) In an effort to integrate the influence of environmental variables on bivalve growth a number of mathematical "carrying capacity" models have been developed that estimate the standing stock at which commercial harvests are maximized. This emphasis means that other important aspects of ecosystem carrying capacity, such as the ability of the culture site to process the excrement produced by the animals, may not be adequately modeled. I recommend that an open source- code community model be developed to assess "ecological carrying capacity" for bivalve aquaculture. The overall objective should be to develop a well-parameterized model that will allow a comprehensive assessment of the major interactions between cultivated bivalves and the ecosystem. For example, in addition to predicting tissue production, this model can be used to assess the ability of suspension-feeding bivalves to exert top-down control on phytoplankton stocks, reduce turbidity, enhance nutrient removal, and provide habitat for other organisms. These secondary benefits can have economic value to the aquaculturists as part of polyculture systems, environmental remediation, and nutrient trading schemes. By modeling major aspects of ecosystem function, such as competition for food with other suspension feeding organisms, rates and location of biodeposition etc., models can be used to predict and possibly minimize potential adverse effects of bivalve aquaculture.

Key Words: Aquaculture, Bivalves, Carrying Capacity, Nutrient Removal, Polyculture

INTRODUCTION

All models are wrong. Some models are useful (DiToro 2001)

Commercial aquaculture of suspension-feeding bivalve molluscs, such as oysters and mussels, can benefit from quantitative estimates of how much production can be obtained from a location. The number of individuals that have to be stocked to achieve this maximum production is often simply referred to as the "carrying capacity." Carrying capacity is quite a widely-used term in biological science and, confusingly, has acquired a number of different meanings. Originally, it was a concept in ecology that was applied to the population density achieved at the asymptote in the logistic population growth equation (Odum 1983, Dame and Prins 1998). More recently, the term has broadly come to mean the maximum biomass that can be sustained

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by the available resources (Odum 1983). This ecosystem-based concept forms the basis of Carver and Mallet's (1990) definition of carrying capacity as the maximum standing stock of a particular cultured species at which production is maximized without negatively affecting growth rates. That definition may not always apply to commercial aquaculture, however, because production may be maximal even though individual growth rates are low (Smaal *et al.* 1998). Because of such inconsistencies, Smaal *et al.* (1998) proposed a definition for aquacultural production where "exploitation carrying capacity is the stock size at which a maximum yield of the marketable cohort is achieved."

Estimating "exploitation carrying capacity" for aquaculture sites in the natural environment, and thereby assessing potential economic returns prior to establishing an aquaculture operation is difficult. This is because food availability, which is one of the prime factors governing bivalve growth, is spatially and temporally variable because of changes in rates of phytoplankton production and water currents that regulate "food flux" through the grow-out sites (Wildish and Kristmanson 1997, Bacher *et al.* 2003). In an effort to integrate these complex environmental variables a number of different "carrying capacity" models have been specifically developed in order to predict optimum bivalve stocking densities (e.g., Bacher *et al.* 1997, Dowd 1997, Campbell and Newell 1998, Smaal *et al.*1998, Chen *et al.*1999, Bacher *et al.* 2003, Duarte *et al.* 2003, Nunes *et al.* 2003).

Restricting models to predicting the stocking density that maximize harvest yields means that there is no consideration of possibly adverse effects of the cultivated bivalves on important aspects of ecosystem function, such as the ability of the culture site to process excrement. In addition, possible ecosystem benefits are not modeled, such as bivalves feeding on phytoplankton and in the process removing nutrients from the water column (Newell 2004). This concept is the basis of integrated "ecological" or "balanced ecosystem" aquaculture operations (McVey *et al.* 2002, Neori *et al.* 2004) in which commercially valuable species from different trophic levels (e.g., algae and bivalves) are cultured so that they "extract" nutrients that are being added elsewhere into the system (e.g., from finfish that are intensively fed). Furthermore, in some countries (e.g., USA) there is a move toward nutrient trading schemes where industries that pollute aquatic systems with nutrients pay other industries to remove nutrients from the same body of water. It is possible that shellfish aquaculture may qualify for payment under such nutrient trading schemes if the aquaculture facility is managed in such a way to maximize nutrient removal (Newell 2004). Only by developing predictive models will it be possible to design systems that maximize levels of nutrient removal.

In order to accommodate this broader ecosystem perspective, I propose that "ecological carrying capacity" for bivalve aquaculture be defined as "The standing stock of suspension-feeding bivalves where the consumption of phytoplankton, enhancement of nutrient removal, and other ecosystem services are maximized without negatively affecting water quality, sediment biogeochemistry, and overall ecosystem function." This is similar to the definition of carrying capacity proposed by Duarte *et al.* (2003) of "the level to which a process or variable may be changed within a particular ecosystem, without driving the structure and function of the ecosystem over acceptable limits." Both definitions suffer from ambiguous definitions of an unacceptable outcome (i.e., "without negatively affecting" and "over acceptable limits.") It is necessary for there to be greater discussion as to what constitutes the proper criteria and methods for assessing "ecosystem influence." It is overly optimistic to think that any aquaculture operation will have no adverse impacts whatsoever; consequently, the question becomes what level of impact is considered acceptable given the benefits accrued from that activity. Ultimately because that is a societal, and not an objective scientific question, the acceptable levels will likely vary from country to country.

Some criteria for monitoring ecosystem influences of bivalve aquaculture have been developed and can be used both as modeling criteria and then objectively measured in field situations. For example, Grant *et al.* (1995) performed a detailed study of a mussel aquaculture site and used a sophisticated benthic faunal analysis and measurements of sediment biogeochemistry to quantify ecosystem impacts. Both of these criteria are highly sensitive to sediment redox balance. The depth of the redox potential discontinuity (RPD) in sediments can be measured directly, either in sediment cores collected in transparent acrylic plastic tubes (Grizzle and Penniman 1991), or by using a remotely operated camera system that directly photographs the sediment profile (O' Connor *et al.* 1989). This photographic technique can also provide quantitative information on changes in the infaunal macrofauna community. These criteria are similar to those adopted in Japan, where the accumulation of acid volatile sulfide in the sediment and changes in macrofauna abundance are used to monitor the influence of fin fish cultivation on the surrounding environment (Yokoyama 2003). This approach of objectively specifying certain key ecosystem processes and then monitoring these at aquaculture sites allows deviation from predetermined values for each variable to be discerned. These key ecosystem processes can also be incorporated as output parameters in a model to predict the effects of balanced aquaculture on the ecosystem.

The objective of this paper is to provide a framework to help stimulate a discussion of what should be included in future "ecological carrying capacity models" for bivalve aquaculture. This model should only include the essential elements as it would be counterproductive to develop an overly complex model, with time spent parameterizing details that do little to improve the overall accuracy of the model predications. I briefly review here some of the information that needs be included for the main four ecosystem processes that suspension-feeding bivalves influence: 1) top-down control on phytoplankton and microzooplankton; 2) sediment hypoxia; 3) inorganic nutrient cycling; 4) reduction in turbidity. I also briefly draw attention to the fact that the culture gear (rafts, cages, ropes, etc.) and the animals themselves can provide important habitat for other ecologically valuable "fouling community" organisms. Transfer of organic material to the sediment surface in biodeposits may also stimulate benthic production. Such effects on secondary production, and the likely transfer of this production to higher trophic levels, are difficult to model but can be important ecosystem benefits of bivalve aquaculture systems.

MODEL COMPONENTS

1) Top-down control on phytoplankton and microzooplankton

Suspension-feeding bivalves remove particles > 3 μm diameter from the water column with high efficiency when water temperatures are high enough to promote activity (Bayne and Newell 1983). This feeding activity can have the beneficial effect of exerting exert top-down control on phytoplankton populations that may be stimulated by nutrient inputs from point and diffuse terrestrial sources, adjacent fin-fish aquaculture sites, etc. (Newell 2004, Newell *et al.* 2005). Bivalves, by directly grazing on microzooplankton, may also reduce the dominance of carbon flow through "microbial loop" pathways (Sherr and Sherr 1988, Kreeger and Newell 1997, Kamiyama 2004).

Size selective feeding by bivalves means that larger nanoplankton cells (>3 μm diameter) are preferentially removed in comparison with smaller and less efficiently retained picoplankton species. In order to accurately model the food resources available to suspension-feeding bivalves in any particular location, the size structure of the phytoplankton and microzooplankton community needs to be assessed. This will require models to include size-specific rates of phytoplankton production rather than use total chlorophyll *a* concentrations as a proxy for food available to bivalves, which is the approach adopted in many existing bivalve carrying capacity models (Campbell and Newell 1998, Smaal *et al.* 1998, Nunes *et al.* 2003, Duarte *et al.* 2003). Furthermore, differential grazing by bivalves can lead to the situation where picoplankton species are subject to reduced grazer control compared to larger species and hence become relatively more abundant (Olsson *et al.* 1992, Prins *et al.* 1998). Such an increase in picoplankton was documented by Vaquer *et al.* (1996) and Souchu *et al.* (2001) in a poorly flushed lagoon in the Mediterranean that has high abundances of aquacultured bivalves.

An additional reason for not simply using total chlorophyll as an estimate of food availability is that some species of phytoplankton possess toxins that reduce bivalve feeding activity (Shumway 1990). It is thought that blooms of such toxin producing algae may be increasing in distribution and frequency worldwide and anthropogenic nutrient enrichment is a likely causal factor (Cloern 2001). Even if the algal toxins do not adversely affect the bivalves directly, toxins can be bioaccumulated to levels that render the flesh unsafe for human consumption (Shumway 1990). Because the exact causes of harmful algal blooms are uncertain, it will be difficult to incorporate their occurrence into predictive ecosystem models but that does not mean that their influence should be ignored.

There can also be deleterious ecosystem effects of high rates of phytoplankton removal by suspension-feeding bivalves. At high bivalve densities there can be intraspecific competition for food that can be partially reduced by configuring the culture system to increase water through the site, thereby minimizing refiltration. This purely physical influence of water flow on food flux can now be efficiently modeled using coupled physical and biogeochemical models (e.g., Campbell and Newell 1998, Chen *et al.* 1999, Duarte et al. 2003). Interspecific food competition between high abundances of cultured bivalves and other ecologically valuable benthic and pelagic suspension-feeders (e.g., zooplankton) should be modeled explicitly. For example Lam-Hoai *et al.* (1997) reported that in areas with shellfish aquaculture there were appreciable differences in abundances of 40 to 300 μm diameter microzooplankton compared to areas with no aquaculture farms. They ascribed these differences in community structure to microzooplankton being directly grazed by bivalves and by other suspension-feeding invertebrates attached to the aquaculture structures. Bivalves may also out-compete some types of zooplankton for phytoplankton because bivalves overwinter as adults and are able to start feeding when water temperatures reach the threshold necessary to promote an active metabolism. In contrast, temperate copepod species, that form a dominant component of the zooplankton, rely on a relatively small number of adults to survive overwinter that can then feed and reproduce in order to rebuild the population. As discussed above, bivalve grazing may alter phytoplankton species and size composition and thereby affect the food resources available to other benthic and pelagic suspension-feeding fauna.

2) Sediment hypoxia

Aquacultured finfish require an external food source and this feeding results in the addition to the water surrounding the aquaculture facility of "new" dissolved inorganic nutrients from fish urine and feces that can stimulate high levels of phytoplankton production. The situation is very different for bivalve aquaculture because the dissolved and particulate excrement released to the environment by bivalves is solely from them consuming autochthonous production that utilizes ambient dissolved inorganic nutrients. However, potentially adverse effects from both finfish and shellfish aquaculture facilities can result from excess deposition of fecal material that may overload the underlying sediments with particulate organic material. Bacterial decomposition of this organic material can release more inorganic nutrients and in extreme situations cause sediment anoxia, thereby reducing the biomass and species diversity of benthic fauna.

Undigested organic material in the feces and pseudofeces of bivalves are voided as mucus-bound pellets (collectively called biodeposits) that can be as long as several millimeters. As a consequence of this aggregation, biodeposits have a faster sinking velocity that is up to 40 times that of the component particles (Widdows *et al.* 1998). These biodeposits settle where the friction velocity (u^*), which is a function of current velocity and bed roughness, is below a critical velocity required to suspend particles of that particular mass (Miller *et al.* 2002). In locations with sufficient physical mixing, biodeposits can become disaggregated into smaller particles that sink more slowly and are resuspended at lower friction velocities. Where bottom friction velocities remain below the critical erosion velocity, biodeposits undergo a consolidation process and become incorporated into the sediments around the bivalve population, hence increasing particulate and dissolved nutrient concentrations within that zone (Kaspar *et al.* 1985, Miller *et al.* 2002).

Because bivalves filter phytoplankton from large volumes of water, and these biodeposits are voided in the relatively small region around the aquaculture site, bivalves do serve to concentrate and focus nutrients (for review see Newell *et al.* 2005). Food-based carrying capacity models (e.g., Smaal *et al.* 1998, Duarte *et al.* 2003, Nunes *et al.* 2003) can predict the locations with the highest phytoplankton production that can support the greatest density of aquacultured bivalves. Unfortunately, in such productive locations bivalves can be stocked at such high densities that their biodeposits are focused onto a small area of sediments. When receiving sediments become overloaded with organic material the resulting bacterial respiration can consume oxygen at rates faster that it can be resupplied by diffusion. In such circumstances anaerobic microbial pathways dominate, and sulfur reducing bacteria produce high levels of hydrogen sulfide that are toxic to benthic infaunal species (Diaz and Rosenberg 1995). This loss of infauna exacerbates the adverse effects of excessive biodeposition on sediment biogeochemical processes because of a reduction in bioturbation processes that serve to bring oxygen into the sediments (Aller 2001, DiToro 2001). Loss of infauna also reduces food resources for carnivores at higher trophic levels.

Understanding and modeling the biotic and abiotic changes in the receiving sediments associated with organic loading from bivalve excrement is necessary in order to accurately parameterize "shellfish ecological carrying capacity models." Accurately modeling water flow is especially critical since strong water currents can distribute bivalve biodeposits widely over the bottom, hence reducing their adverse effects on sediment. Water flow is also crucial in supplying oxygenated water to hypoxic sediments.

3) Inorganic nutrient cycling

Nutrients incorporated in phytoplankton biomass are filtered from the water column by bivalves, ingested, and digested in seasons when water temperatures are warm enough to promote active feeding. Nutrients that are digested but not assimilated are excreted and returned to the water column nutrient pool. A majority of the nitrogen is excreted in the form of ammonium and this may have a stimulative effect on local phytoplankton production (Dame 1996, Newell *et al.* 2005).

Undigested organic material is transferred to the sediment surface in biodeposits where it is degraded through complex microbial processes (DiToro 2001, Newell *et al.* 2002). A large proportion of the nitrogen (N) and phosphorus (P) is regenerated back to the water column (Newell *et al.* 2005). Inorganic nutrient regeneration from the sediments is not 100% efficient, however, which leads to the loss of some nutrients each time phytoplankton are consumed by bivalves and the resulting biodeposits transferred to the sediment surface. Where sediments remain oxygenated, some of the P that was originally incorporated in phytoplankton, but was not digested by the bivalves, can become sequestered and buried as iron-bound complexes. Where biodeposits are incorporated in aerobic surficial sediments that overlay deeper anaerobic sediments, microbially mediated coupled nitrifica tion-denitrification can remove as N_2 gas some of the nitrogen that was originally incorporated in phytoplankton. Some N can also become buried in the accumulating sediments. In locations with sufficient light at the sediment surface, however, benthic microalgae compete with nitrifying bacteria for N regenerated from the bivalve biodeposits, thereby reducing or even precluding coupled nitr ification-denitrification (Newell *et al.* 2002). If the sediments become anaerobic, coupled nitrification-de nitrification is inhibited, P is mobilized and released to the water column, and the resulting build-up of H_2S can be toxic to other benthic animals. Loss of these bioturbating fauna reduces sediment irrigation that is an important mechanism for sediment oxygenation, and hence further increases the likelihood that the sediment will remain anoxic.

Duarte *et al.* (2003) suggested that spatially explicit hydrological models be used as the basis of carrying capacity models. By modeling water flow and food fluxes the optimum spatial distribution of aquaculture farms within coastal systems may be accurately predicted. The influence of the aquaculture systems themselves (rafts, ropes, etc.) in imposing drag, and hence reducing water flow, also needs to be considered (Grant and Bacher 2001). Better information on water currents also means that the possible distribution of biodeposits over the surrounding sediment surface can be predicted. This distributional data, when linked with information on the biotic and abiotic characteristics of the receiving sediment (e.g., grain size, porosity, influence of periodic storms in scouring bottom sediment, etc.) will allow the influence of biodeposition on sediment biogeochemistry and benthic organisms to be modeled (DiToro 2001). Information on rates of nutrient regeneration, burial, and denitrification becomes even more crucial if bivalves are being cultivated as part of a poylculture system in order to enhance nutrient removal (Newell 2004).

4) Reduction in turbidity

In locations with high bivalve biomass and relatively restricted water exchange with surrounding waters, the feeding activity of bivalves can remove sufficient organic and inorganic seston particles that the amount of light reaching the sediment surface is increased. This has the effect of reducing the dominance of phytoplankton production and extending the depth to which ecologically important benthic plants, such as seagrasses and benthic microalgae, can grow. Newell and Koch (2004) developed a simple model of the effects of suspension-feeding bivalves on altering light penetration and the consequent benefits to seagrass beds. Their model showed that reestablishing seagrass beds may be facilitated by first rebuilding depleted oyster stocks to increase light penetration. It is apparent that aquacultured oysters could provide similar improvements to water clarity, therefore potentially allowing management authorities to permit aquaculture in regions generally considered too ecologically sensitive for such commercial uses. It has been shown, however, that there are severe reductions in seagrass beds in the immediate vicinity of oysters cultivated on the bottom in Oregon, USA. The causes of this seagrass loss were multifaceted, including direct shading by the aquaculture gear, enhanced biodeposition reducing sediment suitability for seagrasses, sediment erosion associated with on-bottom racks altering bottom water currents, and severe disturbance associated with husbandry activities (Everett *et al.* 1995).

A potential adverse effect of an increase in light at the sediment surface is that nuisance macroalgae may become established, rather than a more normal flora of seagrasses and microphytobenthos. Some types of macroalgae (e.g., Cladophora spp.) flourish in locations that have elevated levels of inorganic nutrients and relatively low irradiances (from 18 to 175 μmol photons^{-2} s^{-1}), and under such conditions can out-compete other macroalgae (Rafaelli *et al.*1998).

5) Provision of food resources and habitat for other organisms.

Bivalve biodeposits have a high residual organic content, with a C:N ratio similar to phytoplankton (Newell *et al.* 2005), and can therefore provide a nutritious food source for benthic deposit feeders. An increase in sediment organic N content has frequently been observed near large aggregations of bivalves (Kaspar *et al.* 1985, Kautsky and Evans 1987, Deslous-Paoli *et al.* 1992, Hatcher *et al.* 1994, Stenton-Dozey *et al.* 2001). The type of response observed in benthic communities adjacent to bivalve stocks is very dependent on the magnitude of sediment enrichment by biodeposits. The degree of enrichment is governed not only by the abundance of bivalves but also the area of bottom over which their biodeposits are distributed, which is dependent on the magnitude of water currents and wave action (Miller *et al.* 2002, Newell 2004). As discussed above, high levels of biodeposition can stimulate sediment microbial metabolism to the point that oxygen becomes limiting. At this point bacterial anaerobic metabolic pathways start to generate toxic hydrogen sulfide (Aller 2001).

In response to low to moderate organic loadings by bivalves, species diversity and biomass of meiofauna and macrofauna deposit feeders are often increased compared to areas without bivalves (Kautsky and Evans 1987, Dittmann 1990, Ragnarsson and Raffaelli 1999). Grant *et al.* (1995) reported relatively minor changes in macrobenthic biomass and diversity associated with biodeposition from suspended mussel culture. The benthic community underlying intensive rope-cultivation of mussels has often been observed to change from one with a diverse species composition to one composed predominately of infaunal polychaetes (e.g., Kaspar *et al.* 1985, Stenton-Dozey *et al.* 2001). Increases in polychaetes can leads to enhanced bioturbation which has the beneficial effects of increasing rates of coupled nitrification-denitrification compared with the control sites (Kaspar *et al.* 1985). Tenore *et al.* (1982) reported that excessive biodeposition from a high density of mussel aquaculture rafts changed the benthic infauna from one with high species diversity and biomass to one characteristic of a pioneering community, with low species diversity and biomass. There was also reduction in bioturbation associated with the loss of the diverse infaunal community as the dominant species in the pioneering community were tube-building worms with little influence on sediment vertical mixing and sediment irrigation. These types of secondary effects from shellfish aquaculture are difficult to model because the responses are so variable between locations. In order to capture at least some of these ecosystem changes, three-dimensional physical models can be used to predict the amount and spatial distribution of organic material transferred to the sediment surface. Models of sediment biogeochemical processes (DiToro 2001) can be used to predict the depth of oxygen penetration into the sediment and this used to predict if there will be negative effect on infauna. In locations where sediments remain aerobic it will be possible to predict the amount of organic material available to be supplied to the benthic deposit feeder community and this can then be used to estimate rates of carbon transfer to higher trophic levels.

An important ecosystem benefit of natural shellfish beds is that they provide habitat for many invertebrate and vertebrate species (Coen *et al.* 1999, Ragnarsson and Raffaelli 1999, Peterson *et al.* 2003). Dealteris *et al.* (2004) have shown that both on-bottom and off-bottom aquaculture holding gear also provides the type of spatially complex habitat that is sought by many species of mobile animals. These aquaculture structures provide a surface for plant and animal colonization (Mazouni *et al.* 2001) that then provide a food source for many animals. A simplifying approach for including the provision of habitat in ecosystem models would be to calculate the amount of surface area available to be colonized by plants and animals on the aquaculture system (Dealteris *et al.* 2004). Then using simple empirically derived relationships estimate the amount of biomass that may be present for secondary consumers. Such estimates can then be refined by sampling the aquaculture system once it is in operation to quantify the biomass of plants and animals. The extreme periodic disturbances associated with cultivation and harvest practices, especially those required for on-bottom culture of infaunal bivalves (e.g., Everett *et al.* 1995, Kaiser *et al* 1998), will negatively affect the habitat and should be included in the model.

CONCLUSIONS

I recommend that new "exploitation carrying capacity" models for suspension-feeding bivalve aquaculture be developed that can also serve as "ecological carrying capacity" models. The model should include sufficient detail of major ecosystem processes to predict possible beneficial and negative influences that the aquaculture facility may have on the environment. Properly designed models will allow regulatory authorities to assess the secondary benefits of using bivalves to provide ecosystem services, such as graze phytoplankton and thereby remove some of the excess anthropogenic inorganic nutrients present in many of the world's coastal waters. Modeling rates of nutrient regeneration to the water column and removal is especially relevant to "ecological" or "balanced ecosystem" aquaculture operations where bivalves and seaweed are cultivated to help remove nutrients generated from finfish aquaculture (McVey *et al.* 2002, Neori *et al.* 2004).

Many different research groups have developed carrying capacity models for bivalve mollusc aquaculture. These models, some of which are cited above, have all been undertaken as independent projects and have rarely directly incorporated relationships parameterized for earlier models. I think that it would be advantageous to all concerned if new ecosystem models are developed as open source "community models" that enable free and open access to the relevant code. Community models allow various investigators to parameterize and add in specialized sub-models that ultimately constitute a single, fully parameterized, model. For example, three-dimensional physical models have been developed by Chen *et al.* (1999) that could serve as the central core of a new bivalve aquaculture model. The complex sediment biogeochemical processes that will be affected by bivalves are included in the sophisticated sediment diagenesis model developed by DiToro (2001) which can be added as a component to an aquaculture model. The influence of bivalve on light penetration and the growth of benthic plants could be based on models developed by Alvera-Azcarate *et al.* (2003) for macroalgae and Newell and Koch (2004) for seagrasses. In this way essential elements are gradually incorporated into the core model in order to improve the overall accuracy of the model predications.

The approach I advocate of developing an open source code "Community Model" with well-parameterized compartments has been widely adopted by physical oceanographers, who have developed the Princeton Ocean Model (www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/) and the Regional Ocean Model System (www.marine.rutgers.edu/po/). This approach is also being adopted for ecosystem models. For example, a model is under development for the Chesapeake Bay watershed and estuary that will enable free and open access to source code. This is intended to be a web-based model that will include a base model as well as individual modules covering all aspects of hydrodynamics, ecosystem dynamics, trophic exchanges, and watershed interactions (http://ccmp.chesapeake.org/CCMP/). This approach of developing a community model is more efficient than the current situation where even the most recent and sophisticated bivalve carrying capacity models that have been developed (e.g., Dowd 1997, Campbell and Newell 1998, Chen *et al.*1999, Duarte *et al.* 2003, Nunes *et al.* 2003) are missing some important components. Instead, if the best features from each were combined into a single model, it would provide more useful and robust model predictions about ecosystem effects. There are significant logistical problems that have to be solved before embarking on developing such a community based model. Primarily this will require ensuring that sufficient long-term funding is committed for the support personnel who can maintain model code. Once a model is implemented it must be refined and validated using monitoring data that is frequently required to be collected by regulatory authorities to ensure that the aquaculture facility complies with permit requirements.

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Microbial activity and community structure in a net pen aquaculture area

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Abstract Excess organic matter production from net-pen aquaculture farms operated in open water causes serious seawater pollution. To develop sustainable aquaculture systems we need to consider the mechanisms of organic matter cycling. Microbial communities have very important roles in cycling organic matter in seawater. To elucidate how microbial communities are affected by aquaculture activities, we examined the bacterial activity and community structure in a red sea bream aquaculture area and a neighboring, non-aquaculture, reference area in Gokasho Bay, Japan.

The bacterial activity parameters examined - abundance, production rate, and extracellular hydrolytic enzyme activity- were always higher in the aquaculture area than in the reference area, and these differences were most pronounced in surface waters in summer. The annual mean bacterial abundance and production rate in the aquaculture area were 4.7×10^9 cells L^{-1} and 82 mg C m^{-3} day^{-1}: about 1.4 and 3.5 times, respectively, those in the reference area. The annual bacterial production per unit area was estimated as 608 g C m^{-2} y^{-1} in the aquaculture area. The difference of bacterial production between the two examined areas was 444 g (37 mol) C m^{-2} y^{-1}, which was equivalent to the organic matter loads from fish farming. This fact suggests that bacterial community in seawater could utilize organic matters as much as fish farms released into the surrounding water in this aquaculture area.

The annual mean extracellular leucine aminopeptidase activity (which represents bacterial protein degrading activity) in seawater in the aquaculture area was about twice that in the reference area. On the other hand, the activity of β-glucosidase (which represents polyhydrocarbon degrading activity) in the aquaculture area was about five times that in the reference area, indicating that, overall, β-glucosidase activity was promoted more than leucine aminopeptidase activity. These microbial activity parameters were positively correlated with the organic matter concentrations in the water, suggesting that input of organic matter from the fish farms to the surrounding waters promoted microbial activity.

We examined bacterial community structure in seawater by using a PCR-denaturant gradient gel electrophoresis (DGGE) method based on 16S-rRNA gene fragment fingerprinting. Since the level of leucine aminopeptidase activity was closely correlated with the particulate organic matter concentration, the bacterial community was separated into two categories, particle-associated (>1 μm) and free-living (<1 μm). In the free-living bacterial community, the number of DGGE bands (which corresponded to bacterial species) ranged from 2 to 12, and the DGGE profiles were similar in the aquaculture area and in the reference area. However, some bands identified as representing alpha and gamma proteobacteria were observed only in the aquaculture area from spring to autumn. In the particle-associated bacterial community, the number of DGGE bands was less than in the free-living one, and most of the bacteria were identified as cyanobacteria. However, in summer, when the particle-associated bacterial community had high hydrolytic enzyme activity, bands identified as representing

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the *Cytophaga-Flavobacterium-Bacteroides* group, most isolates of which have the ability to degrade biomacromolecules, were detected in the aquaculture area, together with those of alpha and gamma proteobacteria. These results suggest that the variation in bacterial activity was related to bacterial community structure and that aquaculture activity affects the bacterial community in seawater, both quantitatively and qualitatively.

Key words: Bacterial production, hydrolytic enzyme, particle-associated bacteria, DGGE

Net pen culture is the most common form of fish aquaculture in Japan. Because it is usually conducted in small inlets where water circulation is rather small and a large amount of organic matter is input into the net pen as fish food, it can lead to the formation of harmful algal blooms and oxygen-deficient water masses, which are detrimental to cultured fish (Ministry of Agriculture, Forestry and Fisheries of Japan, 2000). To resolve these problems we first need to elucidate the cycling of the organic matter that is added to the aquaculture area. In a fish cage aquaculture, it is estimated that approximately 80% and 75% of input fish food carbon and nitrogen are released into the environment (Hall *et al.,* 1990, 1992). It is consumed by bacteria directly or after reconstructed to organic matters by phytoplankton. Bacterial production contributes to biological production at higher trophic levels in aquatic ecosystems via bacterivorous nanozooplankton (Carrick *et al.*, 1991; Sanders *et al.*, 1992; Jurgens *et al.*, 1996; Fukami *et al.*, 1999; Wieltschnig *et al.*, 2000). This process is now viewed as an important pathway for the energy and material flow as well as the large-organisms-dominated classic food chain. There have been many studies of the balance of organic matter cycling in aquaculture areas (Tanaka, 1977; Hall *et al.*, 1990, 1992; Foy and Rosell, 1991; Holby and Hall, 1991; Johnsen *et al.*, 1993). However, there have been few studies of microbial activity and its contribution to organic matter cycling in these areas (Moriarty, 1997; Patel *et al.*, 2000; Sakami *et al.*, 2003), though the microbial community plays an important role in degradation and remineralization of organic matters.

Most dissolved organic matter in seawater is polymeric and is degraded mainly by bacterial ectoenzymes. Extracellular hydrolysis is thought to be the limiting step of organic matter degradation in aquatic ecosystems, and therefore ectoenzymatic activity is a good indicator of organic matter degradation by bacterial communities (Chrost, 1990; Chrost *et al.*, 1993). We can expect the quality and quantity of organic matter loaded into an aquaculture area to be different from that in oligotrophic areas where the major organic matter source is phytoplanktonic primary production. The main ingredient of fish food is fishmeal and effluents from fish farms contain large amounts of polymeric nitrogen compounds (Foy and Rosell, 1991; McCaig *et al.*, 1999). Mesocosm studies have reported that protein enrichment triggers a dynamic response in ectoenzymatic activity and population dynamics from the microbial community, whereas enrichment with starch has no effect (Chrost, 1993; Pinhassi *et al.*, 1999). We can also expect the qualitative differences in organic matter between the two areas to lead to differences in bacterial organic matter utilization property indicated by ectoenzymatic activity (Sinsabaugh *et al.*, 1997).

We also need to elucidate structures of microbial communities to understand their qualitative variation. However, there are few studies about whole community structure of bacteria in aquaculture areas because most of bacteria in seawater cannot culture in ordinal bacterial culturing methods (Giovannoni and Rappe, 2000). Because bacteria in seawater are the first organisms that act on organic matters loaded from fish farms, their variations of community structure may become a good indicator to assess effects of aquaculture activities on surrounding environment.

The object of this study is to elucidate how microbial communities are affected by aquaculture. We examined bacterial activity parameters such as abundance, production rate, and extracellular hydrolytic enzyme activity in a red seabream aquaculture area. We found that these parameters were always greater in the aquaculture area than those in the reference area, and positively correlated with the concentrations of organic matter in seawater. We also examined bacterial community structure in seawater and could detect some distinctive bacteria in the aquaculture area in warm water season. These facts indicates that aquaculture activity affects the bacterial community in seawater, both quantitatively and qualitatively.

Materials and methods

Study area Gokasho Bay is located in the Sea of Kumano, which is contiguous with the Pacific Ocean (Fig. 1). The bay's mean depth is 18 m, and its area is 22 km^2. The main current runs into the eastern part of the bay. Intensive fish farms are operated in a small inlet in the western part of the bay, the Hasama-ura inlet. The area where net-pens are set covers about 2×1 km. The major product of this area is red sea bream. In 1999 the annual fish production was 1578 t and the total area of net-pens was 23,000 m^2 (Tokai Regional Agricultural Administration Office, 1999). In 1996 the fish feed added to the Hasama-ura aquaculture area was equivalent to a total of about 2225 t of carbon or 328 t of nitrogen (Yokoyama, 2002). This Hasama-ura aquaculture area often suffers hypoxic water conditions and harmful algal blooms in summer (Toda *et al.*, 1994; Abo and Toda, 1995).

Bacterial abundance, production and ectoenzymatic activity

1. Sampling Water samples were collected from the aquaculture area of Hasama-ura inlet (Stn A, water depth about 18 m) and from the central part of the bay as a reference area (Stn R, water depth about 23 m) monthly from June 1999 to September 2000. Water samples were obtained at depths of 0.5 m, 10 m and 1 m above bottom for bacterial production and ectoenzymatic activity measurements. In addition to them, water samples were also obtained at depths of 2.5 m, 5 m (Stn R, Stn A) and 15 m (Stn R) for measurement of chemical parameters. Because water samples for bacterial production measurement had to be treated quickly after collection, they were collected separately (generally

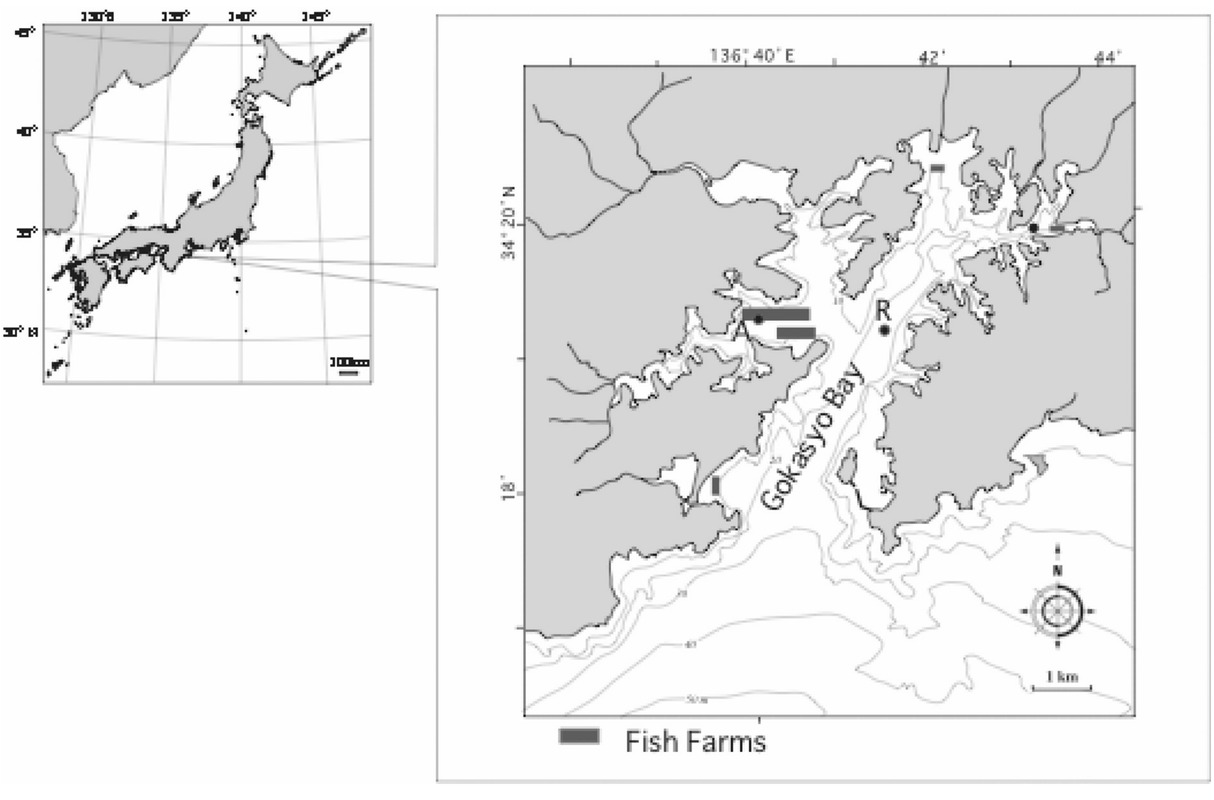

Fig. 1. Map of the Gokasho Bay study area, showing sampling stations.

the next day) from those collected for assessment of ectoenzymatic activity and measurement of chemical parameters. We checked bacterial abundance, chlorophyll-a concentrations and dissolved organic carbon concentrations in both water samples. Water temperature, salinity and chlorophyll-a concentrations were measured *in situ* with a CTD device (Alex, Kobe, Japan). Chlorophyll-a concentrations were calibrated on each sampling occasion by testing 3 or 4 water samples. The chlorophyll-a concentrations were measured by the N, N-dimethyl formamide extraction and fluorescence method (Suzuki and Ishimaru, 1990).

The water samples were carried to a land-based laboratory under cool and dark conditions immediately after collection and treated as described below.

2. Bacterial abundance Samples (30 mL) for assessment of bacterial abundance were preserved with filtered formaldehyde (2% final concentration) and stored at 4 ℃. All samples were analyzed within 1 month of collection. Bacterial abundance was determined by epifluorescence microscopy in DAPI-stained samples collected on 0.2-μm black Nuclepore filters (Porter and Feig, 1980). Duplicate filters were prepared for each sample, and more than 400 cells were counted per filter.

3. Bacterial production Bacterial production was estimated from [^{3}H]-thymidine and [^{14}C]-leucine incorporation rates (Chin-Leo and Kirchman, 1988). Duplicate 5-mL water samples were incubated in the dark at the *in situ* surface water temperature for 30 min with 10 nM [^{3}H]-thymidine and 50 nM [^{14}C]-leucine. Duplicate controls killed with formaldehyde (4% final concentration) were run in tandem with every live incubation. Samples were ice-cooled and precipitated by adding 0.5 mL of ice-cold 50% trichloroacetic acid (TCA) for more than 5 min, then passed through a 0.2-μm membrane filter and washed 3 times with 1mL of 5% ice-cold TCA. Filters were dissolved in 10mL of a scintillation cocktail (Clear-sol Ⅱ, Nacalai tesque, Kyoto, Japan), and radioactivity was read in a liquid scintillation counter (LSC-6101, Aloka, Tokyo Japan). The average difference between the two replicates was 11%.

4. Ectoenzymatic activity To estimate bacterial extracellular hydrolytic activity, we measued the potential activity of two enzymes: β-D-glucosidase and leucine aminopeptidase, which are responsible for the hydrolysis of predominating organic constituents in the dissolved organic carbon pool, i.e., β-linked polysaccharides and proteins (Chrost, 1993).

Aminopeptidase and β-glucosidase activities were measured by using fluorophore-labeled analog substrates, namely L-leucine 7-amino-4-methyl-coumarylaminide (leucine-MCA) and 4-methylumbelliferyl β-D-glucoside (MUF-β-glucoside) respectively (Hoppe, 1983). The substrates were added to duplicate water samples and 1 heat-killed (boiled for 20 min) blank at 4 different concentrations, ranging from 1 to 20 μM for leucine-MCA and 0.04 to 4 μM for MUF-β-glucoside. We chose these substrate concentrations after Rath *et al.* (1993) and from the results of preliminary experiments. The samples were incubated for 1 to 3 h at the *in situ* surface water temperature. Fluorescence was measured with a spectrophotometer (RF-5300PC, Shimadzu, Kyoto, Japan) at 365 nm excitation and 445 nm emission. The average difference between the two replicates was less than 10%. The increase in fluorescence was linear with time for incubation times used. Calibration was performed with standard solutions of 7-amino-4-methylcoumarin and 4-methylumbelliferone. The potential maximum substrate degradation rate (V_{max}) was estimated by the Michaelis-Menten kinetic model (Dowd and Riggs, 1965; Unanue *et al.*, 1999).

5. Chemical analysis Seawater samples for dissolved organic carbon (DOC) analysis were passed through pre-combusted (450℃, 4 h) Whatman GF/F glass-fiber filters. The filtrate was collected directly in muffled glass tubes sealed with Teflon-lined caps, and stored frozen until analysis. DOC concentrations were determined by high-temperature catalytic oxidation using a Shimadzu TOC-5000 analyzer.

Seawater samples for dissolved organic nitrogen (DON) analysis were passed through Whatman GF/F glass-fiber filters and stored frozen until analysis. Dissolved nitrogen was determined as total dissolved nitrogen (TDN), including both DON and dissolved inorganic nitrogen (DIN), by catalytic oxidation followed by chemiluminescent detection of nitric oxide in a Mitsubishi Kasei Corporation TN-05 analyzer. Ammonium, nitrate, and nitrite concentrations were determined by standard colorimetric techniques (Strickland and Parsons, 1977). DON was calculated by subtracting the sum of nitrate plus nitrite and ammonia from TDN.

For particulate organic carbon and nitrogen (POC and PON) determination, seawater samples were passed through pre-combusted (450 ℃, 4 h) Whatman GF/F glass-fiber filters. The filters were dried at 80 ℃ and kept in a desiccator until analysis. POC and PON concentrations were determined by using a CHN analyzer (EA1110; Thermoquest, Milano, Italy).

Particle associated and free-living bacterial communities and their community structure

Since the level of leucine aminopeptidase activity was closely correlated with the particulate organic matter concentration, we separated the bacterial community into two categories, particle-associated (>1 μm) and free-living (<1 μm), and examined their abundance, hydrolytic enzyme activities and community structures respectively.

Water samples were collected at a depth of 0.5 m at Stn A and Stn R monthly from March 2000 to March 2001. Collected water was filtrated through a nucleopore filter of 1 μm pore size with natural gravity. The filtrated fluid was again filtrated through a nucleopore filter of 0.2 μm pore size. Bacterial abundance and extracellular hydrolytic enzyme activity was measured as described above both in the intact seawater sample and the filtrated fluid through 1 μm pore size filter. The abundance and enzymatic activity in the filtrated fluid were regarded as those of free-living bacterial community and the differences between intact seawater and filtrated fluid were regarded as those of particle associated community.

Particles trapped on the filter of 1 μm pore size was regarded as a particle associated community and that on the filter of 0.2 μm pore size was regarded as a free-living community. Each of the filters were put into a NET buffer (400 mM NaCl -20 mM EDTA-50 mM Tris; pH 9.0) and freeze immediately at −80℃ until further analysis. DNA was extracted by phenol-chloroform-isoamyl-alchole mixture and purified by ethanol precipitation. Bacterial 16S-rRNA genes were amplified by PCR using a primer set reported by Muyzer et al. (1993). The amplified gene fragments were analyzed by a denaturant gradient gel electrophoresis method (Muyzer *et al.,* 1993). Denaturant concentrations in the gel ranged from 30 to 60%. Electrophoresis was performed at 110V for 16hours in TAE buffer using the D-Code system (BioRad). The gel was stained by ethydiumbromide and its image was recorded using a Polaroid camera. Some bands were excised from the DGGE gel for sequence analysis. DNA was extracted in distilled water and reamplified. Sequence was determined after cloning using the TA Cloning Kit (Qiagen).

Results

Bacterial abundance, production and ectoenzymatic activity

Water temperature and salinity at both stations showed typical seasonal variations, and the profiles at the 2 stations were almost identical. The temperature ranged from 14.2 to 30.0 ℃ and salinity from 25.37 to 34.78 PSU. These parameters

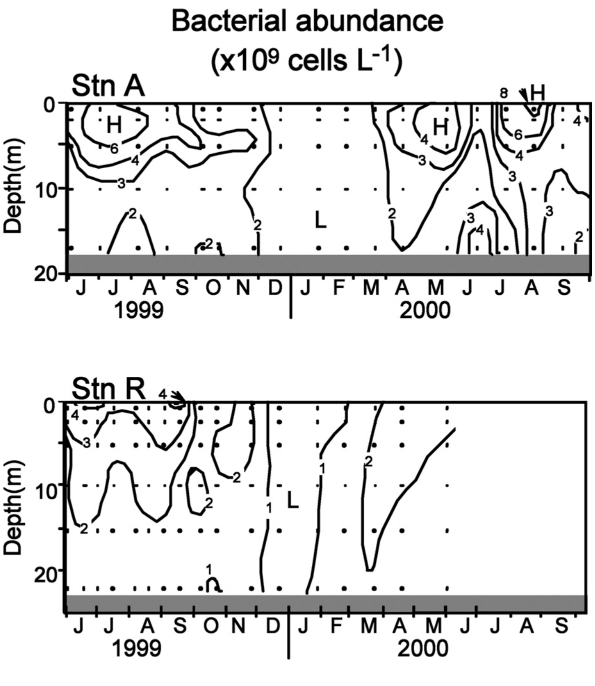

Fig. 2. Isopleth diagrams of seasonal and spatial distribution bacterial abundance in aquaculture area (Stn A) and reference area (Stn R).

indicated that the water column was stratified at around 10 m depth in summer (June to September) and well mixed in winter (October to May).

Bacterial abundance exhibited similar profiles at both stations (Fig. 2). It was high in the surface waters in summer (with the exception of June 2000) and vertically uniform in winter. Bacterial abundance at Stn A was significantly higher than that at Stn R ($p < 0.0001$, *t-test*). It ranged from 0.99 to 8.4 (2.4 in annual average) $\times 10^9$ cells L^{-1} at Stn A and from 0.51 to 4.5 (1.8 in annual average) $\times 10^9$ cells L^{-1} at Stn R.

In general, at both stations bacterial production was high in the surface waters in summer, except in August 2000, and vertically uniform in winter (Fig. 3). The thymidine incorporation rates ranged from undetectable (nd) to 144 (23 in annual average) pmol $L^{-1} h^{-1}$ at Stn R and from nd to 436 (85 in annual average) pmol $L^{-1} h^{-1}$ at Stn A. The leucine incorporation rate ranged from 0.04 to 2 (0.64 in annual average) nmol $L^{-1} h^{-1}$ at Stn R and from 0.18 to 9.2 (1.9 in annual average) nmol $L^{-1} h^{-1}$ at Stn A.

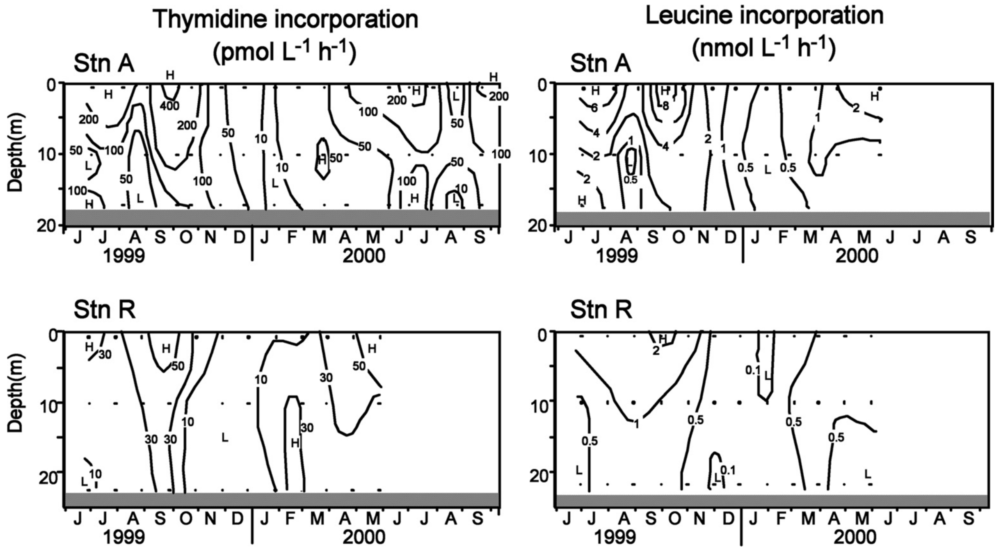

Fig. 3. Isopleth diagrams of seasonal and spatial distribution of thymidine and leucine incorporation rate in aquaculture area (Stn A) and reference area (Stn R).

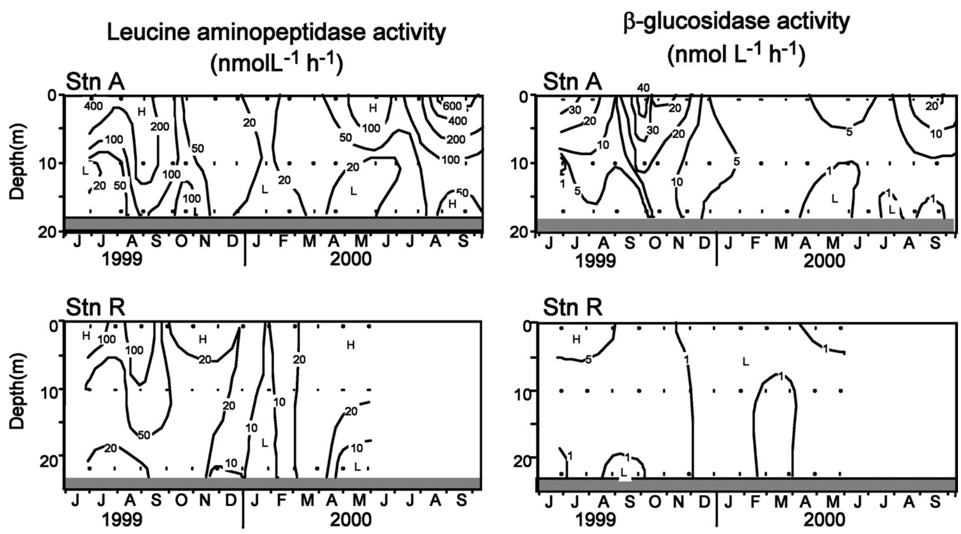

Fig. 4. Isopleth diagrams of seasonal and spatial distribution of leucine aminopeptidase and β-glucosidase activity in aquaculture area (Stn A) and reference area (Stn R).

The bacterial production at Stn A was significantly higher than that at Stn R in both of the parameters ($p < 0.0001$ in thymidine incorporation rate and $p=0.0003$ in leucine incorporation rate, *t-test*).

The profiles of potential ectoenzymatic activity were similar to those of bacterial abundance and bacterial production (Fig. 4). The activities were markedly higher in the surface water in summer, and were vertically uniform in winter at both stations. However, high leucine aminopeptidase activity was observed in the bottom waters in October, just after destratification, at Stn A. Leucine aminopeptidase activity ranged from 1.7 to 165 (32 in annual average) nmol $L^{-1} h^{-1}$ at Stn R and from 13 to 604 (74 in annual average) nmol $L^{-1} h^{-1}$ at Stn A, whereas β-glucosidase activity ranged from nd to 9.5 (1.8 in annual average) nmol $L^{-1} h^{-1}$ at Stn R and from 0.4 to 37 (8.9 in annual average) nmol $L^{-1} h^{-1}$ at Stn A. Both of the leucine aminopeptidase and β-glucosidase activities at Stn A were significantly higher than those at Stn R ($p = 0.0004$ in leucine aminopeptidase and $p<0.0001$ in β-glucosidase, *t-test*).

Organic matter concentration at both stations was shown in Table 1. The concentrations of DOC and DON were also high in the surface waters in summer and vertically uniform in winter at both stations. DOC concentrations were in the range from 51 to 116 (76 in annual average) μM at Stn R and 50 to 161 (85 in annual average) μM at Stn A. DON concentrations were in the range of 4.7 to 10 (7.8 in annual average) μM at Stn R and 3.9 to 23 (8.6 in annual average) μM at Stn A. Both of the DOC and DON concentrations were significantly higher at Stn A than at Stn R ($p=0.0002$ in DOC and $p= 0.0245$ in DON, *t-test*).

The profiles of the POC, PON, and chlorophyll-*a* concentrations were different between the two stations. Particulate organic matter concentrations were high in the surface and middle layers in May, June, and October at Stn R, and high in the surface layer in the summer at Stn A. POC concentrations

Table 1. Ranges of values (annual average from June 1999 to May 2000) of estimated parameters related to microbial activity and organic matter concentrations in aquaculture area (Stn A) and reference area (Stn R) of Gokasho Bay. (nd-not detected)

Estimated parameter	Stn A	Stn R
Bacterial abundance (× 10^9 cells L^{-1})	0.99–8.4 (2.4)	0.51–4.5 (1.8)
Thymidine incorporation (pmol $L^{-1} h^{-1}$)	nd–436 (85)	nd–144 (23)
Leucine incorporation (nmol $L^{-1} h^{-1}$)	0.18–9.2 (1.9)	0.04–2 (0.64)
Leucine aminopeptidase activity (nmol $L^{-1} h^{-1}$)	13–604 (74)	1.7–165 (32)
β-Glucosidase activity (nmol $L^{-1} h^{-1}$)	0.4–37 (8.9)	nd–9.5 (1.8)
Dissolved organic carbon (μM)	50–161 (85)	51–116 (76)
Dissolved organic nitrogen (μM)	3.9–23 (8.6)	4.7–10 (7.8)
Particulate organic carbon (μM)	7.5-117 (8.0)	3.3-101 (7.8)
Particulate organic nitrogen (μM)	0.86-18 (1.1)	0.7-14 (1.0)
Chlorophyll-*a* (μg L^{-1})	0.2–45 (4.7)	0.1–26 (3.7)

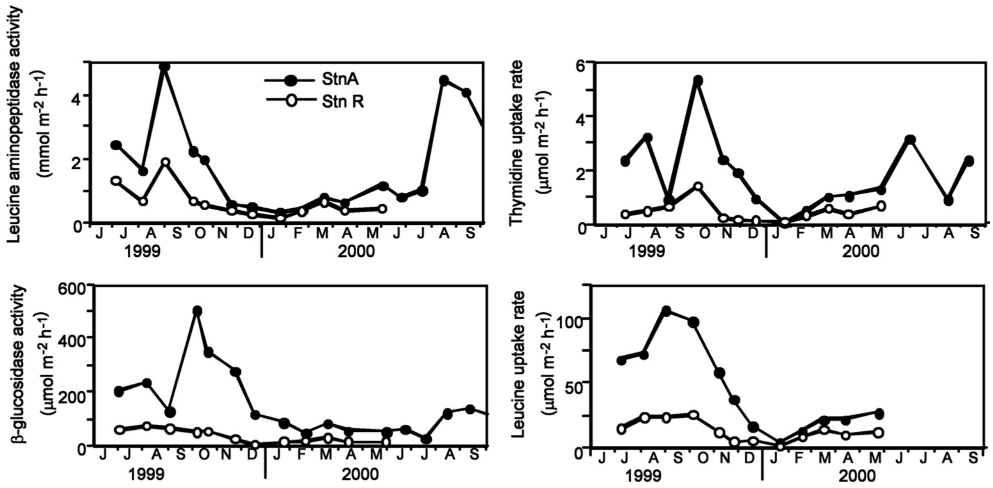

Fig. 5. Seasonal variations in bacterial production and ectoenzymatic activity per unit area in aquaculture area (Stn A; solid symbols) and reference area (Stn R; open symbols).

Table 2. Correlation coefficients between microbial activity parameters and environmental parameters in aquaculture area (Stn A) and reference area (Stn R) of Gokasho Bay. ($P < 0.05$ are shown)

Stn A	DOC	DON	POC	PON	Chl-*a*	Temp	Sal
Bacterial abundance	0.56	0.56	0.77	0.73	0.57	0.61	-0.48
Bacterial production (TdR)	0.44		0.55	0.53	0.40	0.46	-0.77
Leucine aminopeptidase	0.49		0.87	0.86	0.83	0.57	-0.58
β-glucosidase	0.37		0.63	0.62	0.59		-0.54

Stn R	DOC	DON	POC	PON	Chl-*a*	Temp	Sal
Bacterial abundance	0.59	0.42				0.44	
Bacterial production (TdR)	0.36	0.40	0.46	0.50	0.46	0.37	
Leucine aminopeptidase	0.39		0.66	0.67	0.64	0.54	-0.55
β-glucosidase	0.44		0.73	0.70	0.69	0.54	-0.53

TdR: thymidine incorporation rate; DOC / DON: dissolved organic carbon / nitrogen concentration; Chl-*a*: chlorophyll-*a* concentration; POC / PON: particulate organic carbon / nitrogen concentration: Temp: water temperature; Sal: salinity.

were in the range of 3.3 to 101 (7.8 in annual average) μM at Stn R and 7.5 to 117 (8.0 in annual average) μM at Stn A. PON concentrations were in the range of 0.70 to 14 (1.0 in annual average) μM at Stn R and 0.86 to 18 (1.1 in annual average) μM at Stn A. Chlorophyll-a concentrations were in the range of 0.1 to 26 (3.7 in annual average) $\mu g\ L^{-1}$ at Stn R and 0.20 to 45 (4.7 in annual average) $\mu g\ L^{-1}$ at Stn A. Differences in POC, PON, and chlorophyll-a concentrations between the stations were not significant ($p>0.05$, *t-test*).

The annual fluctuations of bacterial production and ectoenzymatic activity per unit area (water column integrated values) are shown in Figure 5. All of these microbial parameters showed greater values at Stn A than at Stn R, especially in late summer/early autumn (August and September). Total annual bacterial production was about three times greater at Stn A than at Stn R in terms of both thymidine and leucine incorporation. Total annual leucine aminopeptidase activity was about twice, and that of β-glucosidase was about five times greater at Stn A than at Stn R.

Statistical analysis indicated that the microbial activity parameters were positively well correlated with organic matter concentrations in the water at both of the stations, with exception of DON at Stn A (Table 2). Comparing the relationship between the two stations, the correlation between POC and bacterial abundance was significantly stronger at Stn A than at Stn R. Bacterial production (TdR) were significantly negatively correlated with salinity (Sal) at Stn A but not at Stn R. Leucine aminopeptidase activity showed a strong positive correlation with particulate organic matters (POC, PON, and Chl a), which was significantly greater than that with DOC at Stn A.

Abundance, hydrolytic enzyme activity and community structure of particle associated and free-living bacterial communities

Bacterial abundance of particle associated community was high in warm water season (Fig. 6). Percentage of particle associated bacterial number to the total bacterial abundance was 20% in average, indicating that free-living community was a major part in view of the abundance. In β-glucosidase activity, percentage of particle associated bacterial community was fluctuated widely but 30% in average, indicating that 70% of the enzyme activity was in the free-living community. On the other hand in leucine aminopeptidase, the particle-associated community was responsible to about 60% of the total activity, and the ratio was greater in summer with the exception of August. This fact agrees with the former observation that leucine aminopeptidase activity was strongly correlated with POM

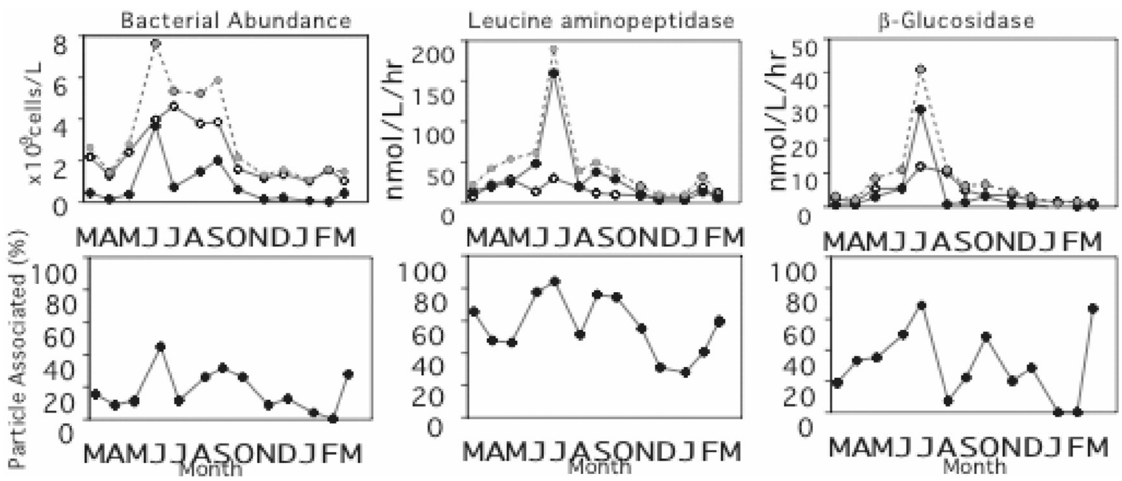

Fig. 6. Bacterial abundance and hydrolytic enzyme activities in total (gray circle with dotted line), particle associated (solid circle), and free-living (open circle) bacterial communities in surface water in aquaculture area (Stn A), and percentage of the values of particle associated community to the total.

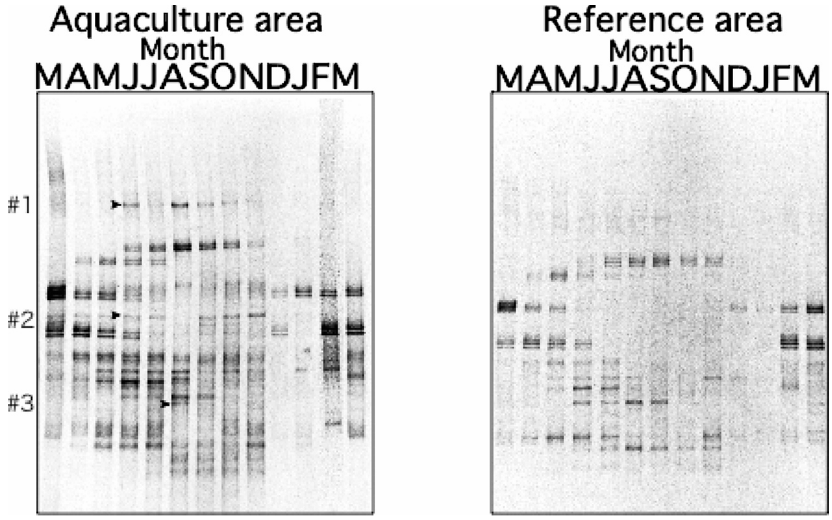

Fig. 7. DGGE profiles of the free-living (<1 μm) bacterial community composition over a year in surface water at aquaculture area and reference area.

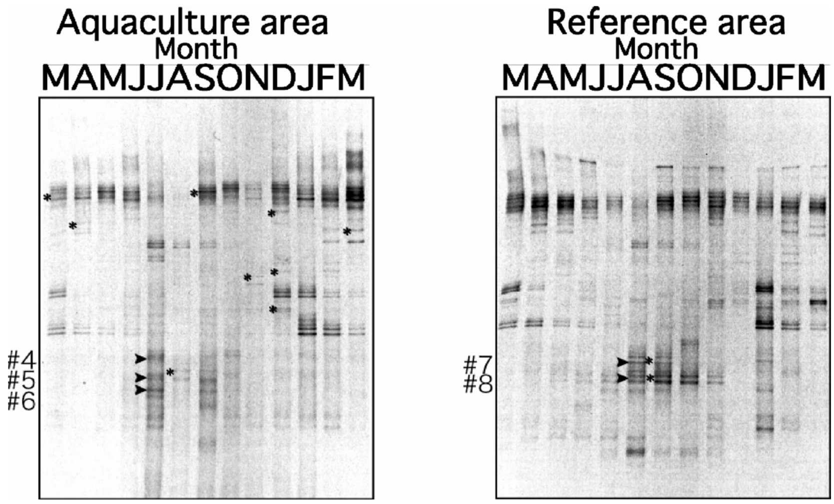

Fig. 8. DGGE profiles of the particle associated (>1 μm) bacterial community composition over a year in surface water at aquaculture area and reference area. Bands marked by star symbols were identified as representing the cyanobacteria.

concentration in the seawater.

In free-living community, the community structure shows clear seasonal variation (Fig. 7). The number of DGGE bands ranged from 2 to 12. The DGGE profile changed obviously between November and December. The DGGE profile in the aquaculture area was similar to that in the reference area. We have confirmed that most of the bands were identical position at both stations in the same month when the samples were loaded on one gel. However, some bands marked by star symbols as #1～#3 in the figure were observed only in the aquaculture area from March to November. From sequence analysis, the band of #1 was identified as representing alpha subclass of the proteobacteria whose closest identified relatives was *Roseovarius* sp.. The band of #2 was as representing gamma subclass of the proteobacteria whose closest identified relatives was *Pseudomonas* sp., and the band of #3 was as representing *Cytophaga-Flavobacterium-Bacteroide*s group whose closest identified relatives was *Cytophaga* sp.

In the particle-associated bacterial community, the number of DGGE bands was less than in the free-living community (Fig. 8). Most of the bands were identified as representing cyanobacteria. In July and September when the particle-associated bacterial community had high hydrolytic enzyme activity, the DGGE profiles were different between aquaculture area and reference area. The bands observed specifically in the aquaculture area in July were identified as representing the *Cytophaga-Flavobacterium-Bacteroides* group (#4), and alpha (#5) and gamma (#6) subclass of the proteobacteria. On the other hand, the bands observed in the reference area (#7, 8) were identified as representing cyanobacteria, indicating that bacterial community composition was different from that in the aquaculture area.

Discussion

Bacterial production in the aquaculture area in Gokasho Bay In this study, we examined annual fluctuation of bacterial production in the aquaculture area and found that the bacterial production was correlated with organic matter concentrations in the water (Table 2) and that it was strongly stimulated in late summer/early autumn (Fig. 5). Yokoyama (2002) has shown seasonal fluctuation of organic carbon and nitrogen load in the form of fish feed into fish cages in this study area. It exhibited a similar pattern with those of bacterial production measured in this study. This fact may suggest that organic matter from fish farms supported the high bacterial production in the aquaculture area. We show the annual mean of organic carbon components in seawater measured in this study in Fig. 9. Bacterial cellular carbon and production was estimated using the ordinal conversion factors; 2×10^{18} cells mol^{-1} thymidine incorporated, and 20 fg C $cell^{-1}$ (Ducklow and Carlson, 1992). It shows that organic matters deposited in the aquaculture area by 9 μM as dissolved organic carbon and by 1 μM as bacterial cellular carbon. Bacterial production rate stimulated due to aquaculture activity (the difference between both stations) was estimated to 5 μmol C L^{-1} day^{-1}. This indicates that potential turn over time of the deposited organic matters in seawater was about 2 days in this aquaculture area.

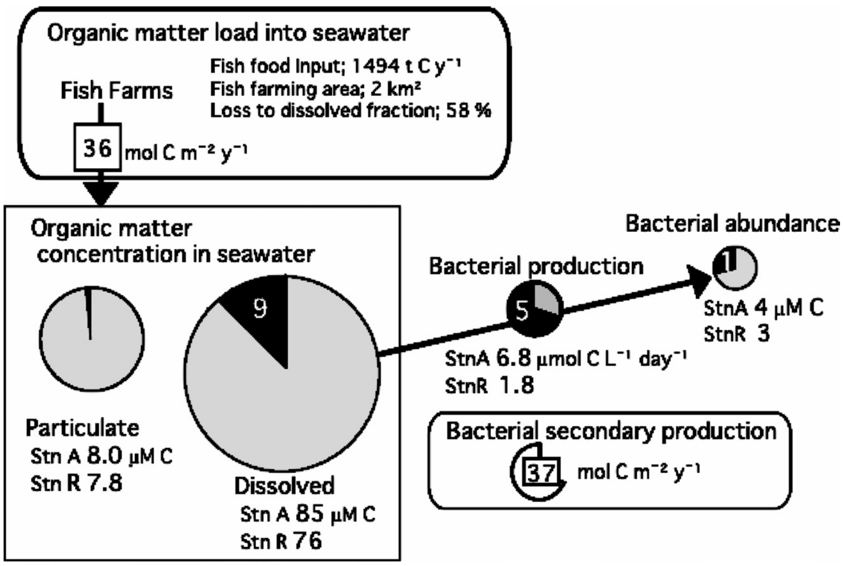

Fig. 9. Mean values of organic matter components in seawater at the aquaculture area (whole circle area) and at the reference area (shaded part), and organic matter input from fish farms.

The Bacterial production rate stimulated due to aquaculture activity was also calculated to be 37 mol C $m^{-2} y^{-1}$ as the sum of depth - integrated values of each month for a year. It was also estimated to be 6.3 mol N $m^{-2} y^{-1}$ in the aquacultrue area, using the conversion factors as C to N ratio of 5.9 (Fukuda *et al.,* 1998). On the other hand, the total amount of fish feed added to this aquaculture area in 1998 was estimated as 1494 t of carbon or 238 t of nitrogen (Yokoyama H, pers. comm. 2001). If the loss to the environment in the dissolved fraction of fish feed is assumed to be 58% for carbon (Hall *et al.,* 1990) or 48% for nitrogen (Hall *et al.,* 1992), then 867 t of carbon and 124 t of nitrogen would have been released into the surrounding water. Considering that the actual fish farming area is 2 km^2, it is calculated that 36 mol C or 4.4 mol N $m^{-2} y^{-1}$ would have been released into the surrounding water. Although these estimations depend heavily on conversion factors translating thymidine incorporation rate into bacterial carbon production (Fukuda *et al.,* 1998) and the extents of the area affected by aquaculture and feed loss, it seems that bacterial secondary production was equivalent to the amount of the organic carbon and nitrogen entering into the water from fish farming.

When the bacterial growth efficiency in the aquacultrue area was assumed to be 0.43 from del Giorgio and Cole's empirical model (del Giorgio and Cole, 1998), the bacterial carbon demand exceeded the carbon input from fish farms. This fact suggests that primary production by phytoplankton might have been also accelerated by the high load of nitrogen and phosphorous from fish farms in this study area. Sakami *et al.* (2003) has shown from a short-term observation conducted at the same study area in summer that the relative bacterial production to the chlorophyll *a* concentration was high only in the deep water in the aquaculture area, but it was invariable in surface to middle water compared with reference area. It seems that most of organic matters released from fish farms utilized by bacteria not directly but after mineralized and reconstructed by phytoplankton. On the other hand, we has shown in this annual study that the chlorophyll *a* concentration in the aquaculture area did not differ significantly from that in the reference area although the bacterial production was much higher in the aquaculture area. Functions of phytoplankton community must be cleared to understand whole organic matter flow in the aquaculture area.

Ectoenzymatic activities in the aquaculture area It should be evident that we measured the V_{max}, which is the estimated maximum enzymatic potential at saturated substrate concentration, not the direct *in situ* activity. Nevertheless, our values for both of the ectoenzymatic activities were within the range of reported activities in eutrophic estuaries (Karner *et al.*, 1992; Rath *et al.,* 1993; Talbot *et al.,* 1997; Nausch *et al,* 1998; Patel *et al.,* 2000). It should also be noted that higher values of leucine aminopeptidase activity, ranging from about 1000 to 4000 nmol $L^{-1} h^{-1}$ have been reported with organic matter enrichment in some mesocosm studies (Chrost and Rai 1993; Pinhassi *et al.,* 1999; Riemann *et al.,* 2000) and in a yellowtail aquaculture area (Patel *et al.,* 2000). The somewhat lower peaks of leucine aminopeptidase activity at the study site (604 nmol $L^{-1} h^{-1}$) may indicate a relatively low organic matter burden in this area.

Seasonal fluctuation of the ratio of β-glucosidase to leucine aminopeptidase activity was shown in Fig. 10. In general, the ratio was always high in the aquaculture area (Stn A) than that in the reference area (Stn R). Especially the ratio was high in the surface water at September, October, and the surface and middle layer water at November when fish food input was high (Yokoyama, 2002). These

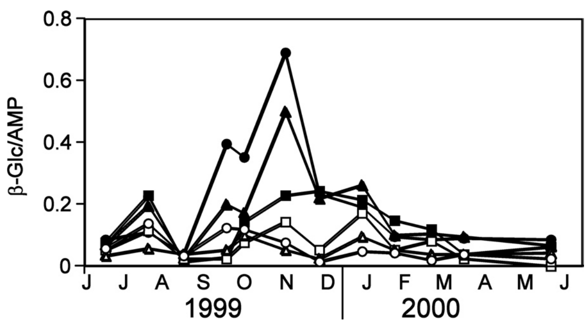

Fig. 10. Seasonal variations in ratio of β-glucosidase (β-Glc) to leucine aminopeptidase (AMP) activity at surface (circle symbols), middle (triangle symbols) and bottom (square symbols) water in aquaculture area (Stn A; solid symbols) and reference area (Stn R; open symbols).

results may indicate that aquaculture activity have stronger stimulatory effect on β-glucosidase activity than on leucine aminopeptidase activity in the aquaculture area. Previous studies have also shown that glucosidase activity is accelerated more prominently than aminopeptidase activity in some eutrophic environments (Chrost and Rai 1993; Rath *et al.,* 1993; Sinsabaugh *et al.,* 1997). On the other hand, some studies also indicated that the synthesis of glucosidase and aminopeptidase in aquatic bacteria is repressed in the presence of low-molecular weight substrates, including inorganic nitrogen, directly available for bacterial metabolism in concentrations that do not limit their growth (Chrost, 1990). Ammonia is the major excretory product of cultured fish and it might repress the aquatic microbial aminopeptidase activity in the aquaculture area. Moreover, if the β-glucosidase activitiy was related to bacterial carbon requirements, the observation that bacterial community in the aquaculture area had relatively higher β-glucosidase activity than leucine aminopeptidase activity might suggest that the bacterial community was under more carbon limit condition than that in the reference area. We measured β-glucosidase activity to assess bacterial extracellular hydrolytic activity because β-linked polysaccharides are a predominating organic constituent of DOC pool in an aquatic environment (Chrost and Rai, 1993). On the other hand, a main carbohydrate ingredient in fish food is flour, which is **α**-linked polysaccharides rich, and β-glucosidase activity does not concern its degradation directly. **α**-Glucosidase activity might promote more in the aquacultrue area than in the case of β-glucosidase.

Particle associated and free-living bacterial community

Leucine aminopeptidase activity was strongly correlated with particulate organic matter or chlorophyll-α concentrations at the aquaculture area (Table 2). The strong relationship between aminopeptidase activity and POM concentration has been reported in several previous studies (Middelboe *et al*., 1995; Talbot *et al*., 1997; Nausch *et al.*, 1998). It has also been shown that particle associated bacterial communities have higher per-cell activity and predominantly degrade the polymeric nitrogen substances on the particle surface where concentration of organic nitrogenous substrate is high (Karner *et al.,* 1992; Hoppe *et al.,* 1988; Smith *et al.,* 1992; Grossart and Simon, 1998; Unanue *et al.,* 1998). We also showed that particle-associated community was responsible for only 20% of abundance but 60% of LAP activity (Fig.6). In summer when their activity was very high, we could observe some specific bacteria and their closest identified relatives were *Pseudomonas* sp., *Cytophaga* sp., and *Bactroides* sp. (Fig. 8). Generally, in the *Cytophaga-Flavobacterium Bacteroides* group, most isolates have the ability to degrade biomacromolecules, such as protein, nucleic acid, and polysaccharide. Its member is expected to have a high organic matter degrading ability. Moreover, beta-subclass proteobacteria group includes a majority of culturable marine bacteria, suggesting that this group may adapt to eutrophic condition (Giovannoni and Rappe, 2000). The bacteria observed particularly in the aquaculture area probably have high organic matter degrading abilities, which explainin the high hydrolytic enzyme activities observed in the aquaculture area.

On the other hand, free-living bacterial community in the aquaculture area was responsible for 80% of abundance and 70% of β-Glc activity in average (Fig. 6). In this community, some specific species (DGGE bands) were also observed in warm water, namely high activity season (Fig. 7). The closest identified relatives of them were *Pelagibacter* (alpha subclass of proteobacteria), *Pseudomonas* (gamma subclass of proteobacteria), and *Bactroides*(*Cytophaga Flavobacterium-Bacteroides* group). They also might have high organic matter degrading ability, especially in β-linked polysaccharides.

In conclusion, we examined microbial community in an aquaculture area and have shown that aquaculture activity affects the microbial community in seawater, both quantitatively and qualitatively. The examined microbial activities were promoted markedly in the aquaculture area and the stimulated bacterial secondary production was estimated to be equivalent to the organic matter loads from fish farming. In the organic matter degrading activity, poly-hydrocarbon degrading activity was promoted more than protein degrading activity. From community structure study, some specific bacterial species were observed at high activity season both in the particle associated and free-living bacterial community. In further study, we need to elucidate dynamics and functions of these particular bacteria to promote a better understanding of effects of aquaculture to the surrounding environment.

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Effect of effluents from a new fish farming site on the benthic environment

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Abstract : In relation to improvement of the environment around fish (red seabream and yellowtail) farms in Shitaba Bay, Uwajima, Ehime Prefecture (Japan), about half of fish cages were shifted from the inside (ca. 20-50 m depth) to the outside (60 m depth) of the bay during May-November 2001. The spatio-temporal variability of the benthic environment at the newly established fish farm site was investigated, by analyzing the sediments at both the new (outside) and the old (inside) farm sites before and after the shift of fish cages. For example, the organic matter load from the new farm was measured to determine the assimilative capacity of the benthic ecosystem.

Acid volatile sulfides (AVS-S) of sediment at the center of the new farm were 0.03 mg/g dry weight in February 2001 without fish cages. As soon as the fish cages were set, AVS-S drastically increased (0.11 mg/g dry weight in July) and reached 0.26 mg/g dry weight in November when the fish cage shift had been completed. Moreover, AVS-S continued to increase and reached its maximum (0.46 mg/g dry weight) in April 2002. However, it remained at ca. 0.3-0.4 mg/g dry weight thereafter. Although AVS-S increased also at the edges and surrounding areas of the new site, concentrations were lower than those at its center. AVS-S increased slightly at areas over 50 m distance from the edges. Total phosphorus (TP) was about 2 times higher in the old farm site than that of the new farm site, while no marked differences of total organic carbon (TOC) and total nitrogen (TN) were detected between the two sites. TN and TP of sediment at the new farm site were slightly higher than concentrations observed in a pearl farm and a non-farming site (as reference sites).

From data on the amount of feed sold, production and feeding amount to cultured fish for some cages, about 50% (5,000 ton in dry weight) of the total amount of feeds sold by the fisheries cooperative association was consumed in the new farm site in 2002. These feeds may be reflected in the TOC, TN and TP flux caught using sediment traps set at 5 m depth above the bottom, which were equivalent to or more than the concentrations at the old farm site.

Thus, it was suggested that the AVS-S increase was largely due to effluent of organic matter (uneaten food and fecal) from fish farming activities closely linked with the shift of fish cages, and that the effect of the loaded organic matter on the benthic ecosystem was low in areas more than 50 m away from fish farming site.

Key words : New fish farming site, Organic matter lord, Benthic environment, AVS-S, TP

Recently, the impacts of coastal aquaculture on the environment become serious problems, and attentions on environmentally sustainable aquaculture production are increasing at local, national and international levels. So it is necessary to clarify the load processes of effluents from aquaculture for evaluating the effects of newly established fish farm sites on the benthic environments. However, few studies have been made so far on this subject in Japan.

In 2001, new fish farming site was established out of Shitaba bay, Uwajima, Ehime, for ensuring and

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promoting sustainable production of cultured fish by avoidance of environmental impact on a limited area. And also, it was estimated that organic matter lord would reduce inside the bay but the benthic environment would change at outside of the bay by increase of organic matter lord. It was expected to work out the environmental control plan of fish farming site, from quantitative relationship between organic matter lord and pollution in fish farming site by investigation of this process of change in detail.

So, the spatio-temporal variability in organic matters loaded from the new fish farm site was investigated, by the analysis of sediments and settling flux at both the new and the old farming sites before and after the shift of fish cages.

Materials and Methods

Shitaba bay is located at western coast of Shikoku Island, Uwajima and characterized by the intermittent inflows of warm water from the "Kuroshio" and cold water from the shelf slope (Takeoka and Yoshimura, 1988; Hashimoto *et al.*, 1995).

Fish farming in this bay started in 1960's, and at first, yellowtail *Seriola quinqueradiata* was the farming fish. Then aquaculture in this bay became more active and now beside yellowtail, red seabream *Pagrus major* and pearl oyster *Pinctada fucata martensii* are the common fish farmed here.

Before the shift of cages, all of them were situated inside the bay, about 20 to 50 m depth and total area of cages were about 43,000 m^2, maximum in regulation. After the shift, about half of cages (21,600 m^2) were set to the new site, which has a depth of about 60 m and other cages (21,382 m^2) were remained inside the bay, and rearranged.

Sampling and data analysis

The changes in benthic environment were investigated at 21 stations in and around of the new fish farming site, the old fish farming site and pearl oyster farming site (Fig. 1). Stn. 6 to 10 were located about 50 m, and stn. 11 to 15 were located about 200 m from edges of the new site.

At the 20 stations among them, sediment samples were obtained using gravity core sampler, for the analysis of acid volatile sulfide (AVS-S). Surface layer (0-1 cm) of AVS-S in sediment was measured with a H_2S absorbent columns (GASTEC, Kanagawa, Japan). Sediment were collected monthly at the stn. 1, 17 and 18 from February 2001 to September 2003 and at the other stations, February, July, September, November in 2001, January, May, July, September, November in 2002 and February, May, August in 2003.

Total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) contents in sediment were analyzed. Sediment samples were obtained in the same way with AVS-S in August and September 2002, at the 5 stations in the new site and 2 stations in the old site. And 2 stations in pearl farming site (Stn. 19, 20) and 1 station outside of the farm sites as a reference site (Stn. 21) were added. Sediments were dried in 60℃ until it became constant weight and sieved with 0.25 mm mesh. After removal of carbonate with HCl (1N), TOC and TN contents were measured with CN coder. TP contents in sediment was measured with the following method. The sediment samples were autoclaved for an hour in a closed bottle with 4% potassium peroxodisulfate solution. The filtrate through GF/F was measured with auto analyzer (BRAN + LUEBBE, Germany).

And also, settling flux of particulate matter was measured with sediment traps (type Montani : Montani *et al*, 1988) set at 5 m above the bottom. At 1 station in the new site (Stn. 16), 1 station in the old site (Stn. 17) and 1 station in the pearl site (Stn. 20) from April 2002 to January 2003 almost monthly. Traps were set in the water during 24 hrs, then taken to the laboratory and settling flux of particulate matter was collected on GF/F filter which was combusted in 450℃ during 2 hrs. The filters were dried in 60℃ until it became constant weight, then weighed. On a part of samples, TOC, TN, TP contents were measured with the same method as the sediment samples.

Feeds consumed to the new and old fish farm site in 2001 and 2002 were calculated from the feed sold data of fishermen's cooperative association, stock number of farming fish and feeding amount to cultured fish for some cages. The monthly amount of feeds to the each sites were calculated from below method.

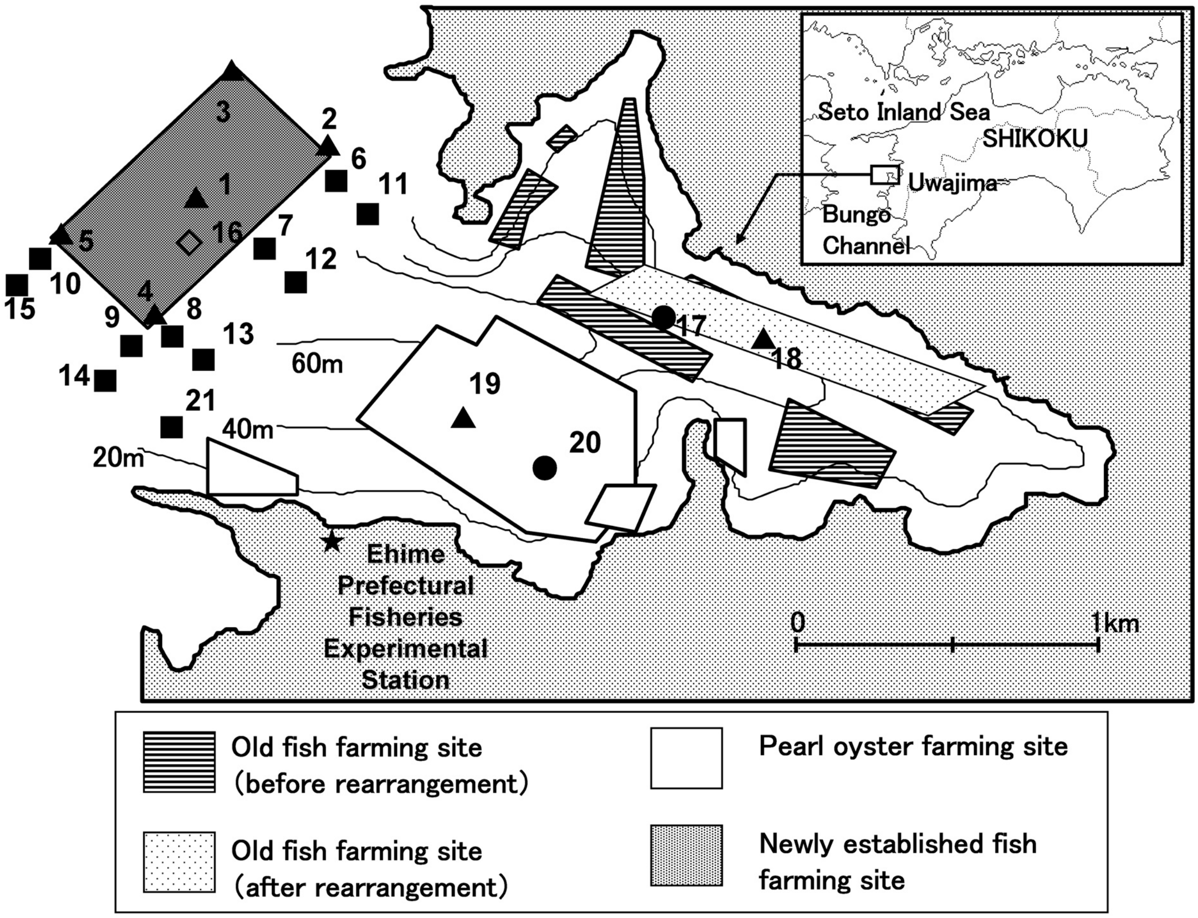

Fig. 1. Map showing sampling stations and farming sites. Stations were shown with following simbols by investigated parametersthere.
● : AVS, TOC, TN, TP and settling flux. ▲ : AVS, TOC, TN and TP
■ : AVS ◇ : Settling flux

$Xn = A \times \Sigma\ (Bij \times Cij) / (\Sigma\ (Bij \times Cij) + \Sigma\ (Bij \times Dij))$

$Xo = A \times \Sigma\ (Bij \times Dij) / (\Sigma\ (Bij \times Cij) + \Sigma\ (Bij \times Dij))$

Xn: Monthly amount of feeds consumed in the new fish farming site.

Xo: Monthly amount of feeds consumed in the old fish farming site.

A: Monthly amount of feeds sold by the fishermen's cooperative association. It was converted to dry weight.

Bij: Monthly feeds consumption by fish kind and age per thousand fish, from some cages. They were converted to dry weight. (Yellow tail was cultured from 2000 to 2002 and red seabream was cultured from 2001 to 2003)

i, yellow tail, red seabream

j, age0, age1+

Cij: Regulation maximum number of fish per cage decided by fishermen's cooperative association × number of cages by fish kind and age in the new fish farming site in September 2002.

i, yellow tail, red seabream

j, age0, age1+

Dij: Regulationary maximum number of fish per cage decided by fishermen's cooperative association × number of cages by fish kind and age in the old fish farming site in September 2002.

i, yellow tail, red seabream

j, age0, age1+

The shift of cages was carried out from May to November in 2001 and it was assumed the cages were shifted in a fixed pace for this period. And the feeds to the new site were calculated by multiplying below number to the monthly feeds with above method.

Mn/7

Mn = progress months number from April (from Jan. to Apr. is 0 ; Nov. and Dec. is 7)

Feeds consumed in the old site for this period were calcultated taking feeds to the new site from monthly feed sold data.

Results

Organic matter lords and AVS-S

Fig. 2 shows the change in AVS-S content of sediment at the newly established fish farming site and surrounding areas from February 2001 to December 2003. At the center of the new site (Stn.1), AVS-S content was 0.03 mg/g dry weight in February 2001 when there was no fish cages. As soon as the fish cages were set in May, AVS-S drastically increased and it reached 0.26 mg/g dry weight in November when the fish cage shift had been completed. Moreover, AVS-S continued to increase and topped in 0.46 mg/g dry weight in April 2002 and after that, it kept about 0.3-0.4 mg/g dry weight until August 2003. AVS-S contents increased in the similar way at the edges and surrounding areas of the new site. But the contents were lower than the center.

Feeds to the new and old fish farming site were estimated for 2001 and 2002. Amount of feeds sold by fishermen's cooperative association were 8,742 dry ton in 2001 and 9,776 dry ton in 2002. But in 2001, when the shift of cages was carried out, there is no data for exactly number of fish cages for calculation of organic matter lord. Monthly feed consumption in the both fish farming sites became minimum in April, then increased until September, and it became almost constant until December, thereafter. This quantitative change of feeds shows similar tendency every year. Moreover, it was estimated about 5,000 ton in dry weight of feeds were consumed in the new site in 2002 after the completion of the shift, this number was nealy equal to the it in the old site in this year. Estimated organic matter lords to the new fish farming site were gradualy increased from May to November in 2001 and AVS-S at Stn. 1 also increased in the similar way of feeds consumption (Fig.3).

Fig. 4 shows a comparison of AVS-S between the center of the new fish farming site and the old site. In the old site AVS-S content was about 0.3-0.5 mg/g dry weight before the shift of cages. Even though after the shift, AVS-S content remained constant for about 3 years in the similar value, it didn't decrease.

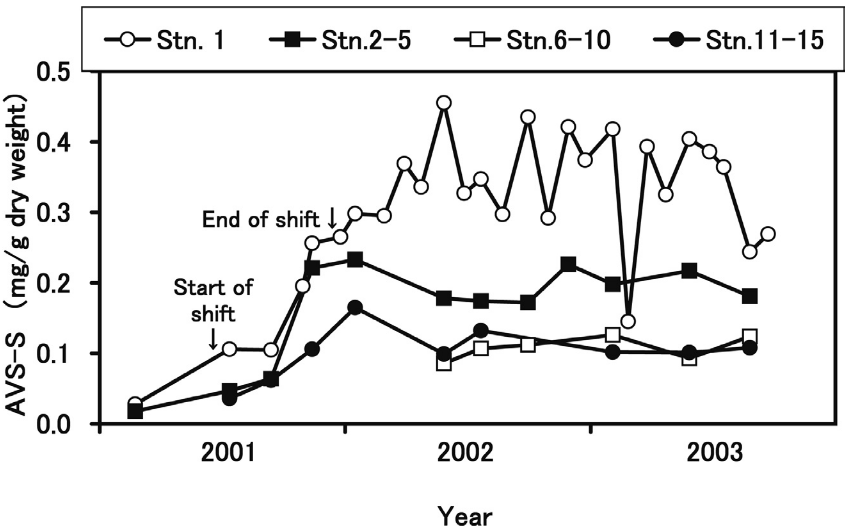

Fig. 2. Change of AVS-S in and around new fish farming site out of Shitaba bay

-○-: Stn. 1 (Center of new fish farming site)

-■-: Average of Stns. 2-5 (Edges of new fish farming site)

-□-: Average of Stns. 6-10 (50m away from the edge of new fish farming site)

-●-: Average of Stns. 11-15 (200m away from the edge of new fish farming site)

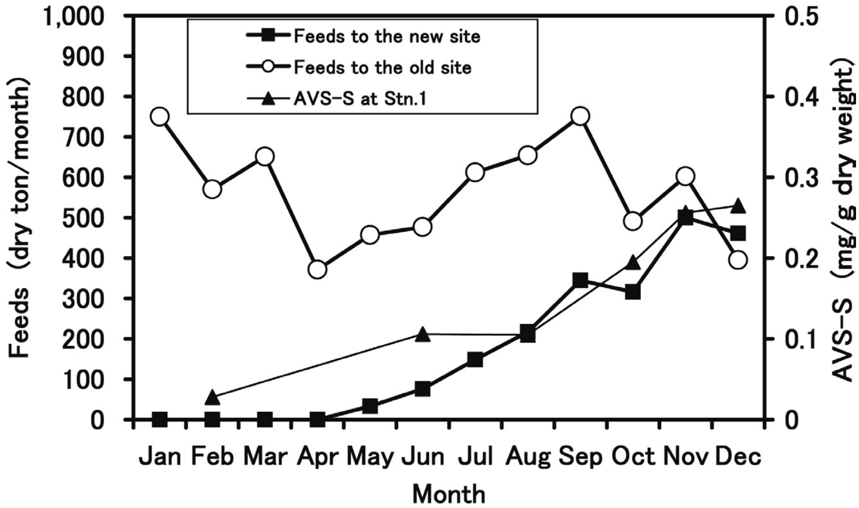

Fig. 3. Change in feeds used to new and former fish farming sites in 2001
Value were converted to dry weight for each site per month.
-■- : Feeds used to new fish farming site per month
-○- : Feeds used to former fish farming site per month
-▲- : Monthly change of AVS-S at Stn. 1

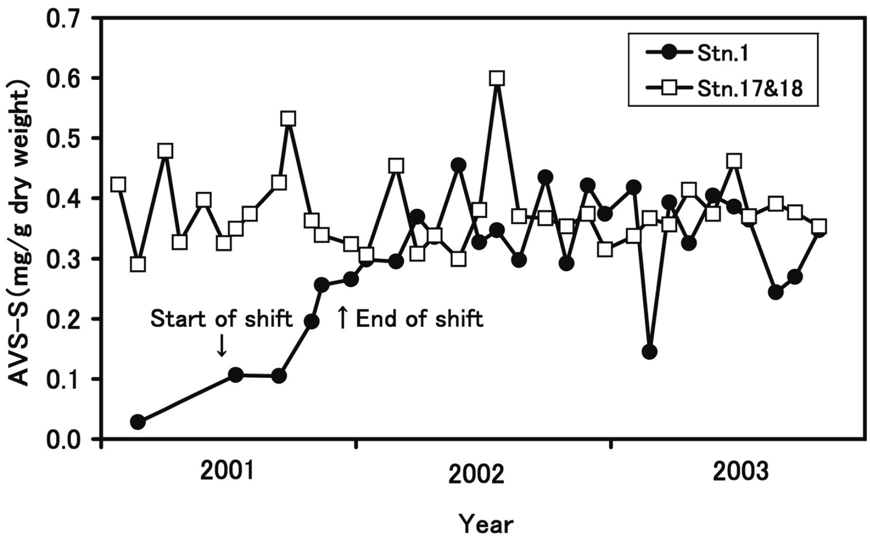

Fig. 4. Change of AVS-S in new and former fish farming sites from january 2001 to August in 2003
-●- : Stn. 1 (Center of new fish farming site)
-□- : Average of Stns. 17 and 18

TOC, TN and TP content in sediment and settling flux

TOC, TN and TP content in sediment have been used for the indicators of artificial effect to benthic environment similarly to AVS-S. TOC content was 14.1-14.5 mg/g dry weight in the new fish farming site, 12.2 mg/g dry weight in the pearl farming site, 13.5 mg/g dry weight in the non-farming site and 15.1 mg/g dry weight in the old fish farming site (Fig. 5). TN content was 1.7-1.8 mg/g dry weight in the new site, 1.5 mg/g dry weight in the pearl site, 1.5 mg/g dry weight in the non-farming site and 2.0 mg/g dry weight in the old site. TP content was 0.6-0.7 mg/g dry weight in the new site, 0.5 mg/g dry weight in the pearl farming site, 0.5 mg/g dry weight in the non-farming site and 1.5 mg/g dry weight in the old site. TP was about two times higher in the old site than the new site. Although, TOC and TN content were slightly higher in the old site, no marked differences were detected between all the sites. In contrast, TP content is remarkably high in only the old site.

The settling flux of TOC, TN and TP was measured from April 2002 to January 2003. Fig. 6 shows TP content among them. TP content in the settling flux was 91-263 mg/m^2/day in the new fish farming site. It increased from April to October, similarly to the trend of feeds amount. In the old fish farming site, TP content in the settling flux topped in 299 mg/m^2/day in December, but it varied widely compared to the new site. And also, the TP content in the settling flux in the new site was higher than in the old site, except for December. On the other hand, TP content in the settling flux in the pearl oyster farming site was lower compared to both fish farming sites, except for May and June. And it was 12-50 mg/m^2/day for the investigation period. TP was higher in the both fish farming sites than the pearl oyster farming site.

Fig. 7 shows the change of TP content in sediment in the old fish, new fish and pearl oyster farming sites from February 2001 to February in 2003. In the old site, though sediment TP was remarkably higher than the other sites in all investigations, it continued to decrease from July 2001. At first, there was no difference between stations in and around the new fish farming site, but at the center of new site, it increased slightly, in contrast to the other stations.

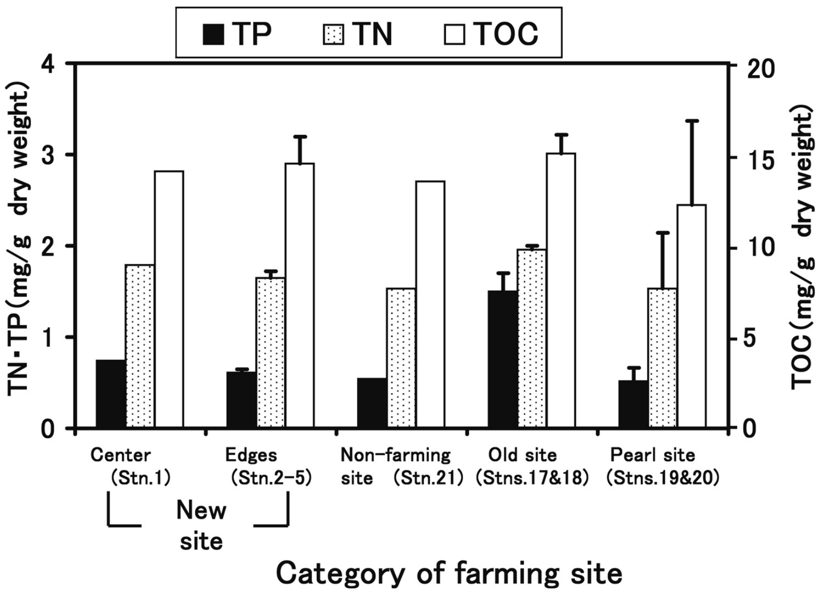

Fig. 5. TOC, TN and TP concentrations in sediment in new fish, former fish and pearl oyster farming sites.

Vertical lines indicate the standard deviations. Samples were collected in August and September in 2002

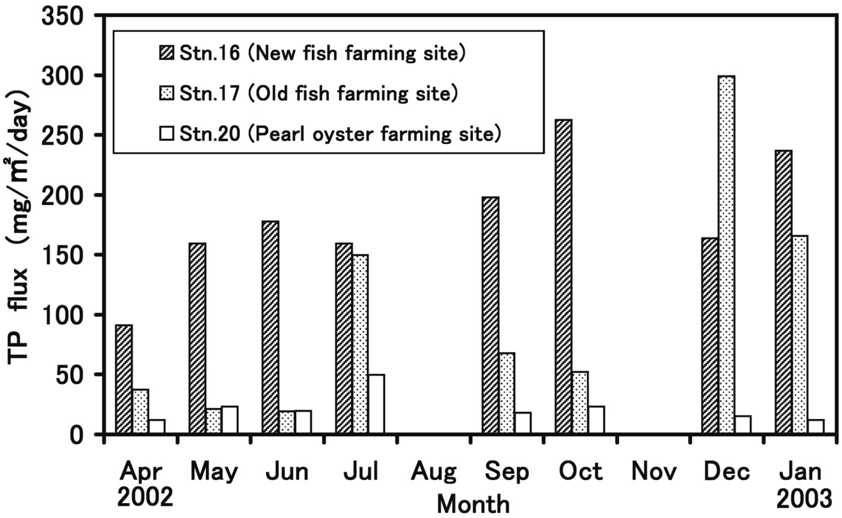

Fig. 6. TP concentration in settling flux to bottom in new fish, former fish and pearl oyster farming sites.

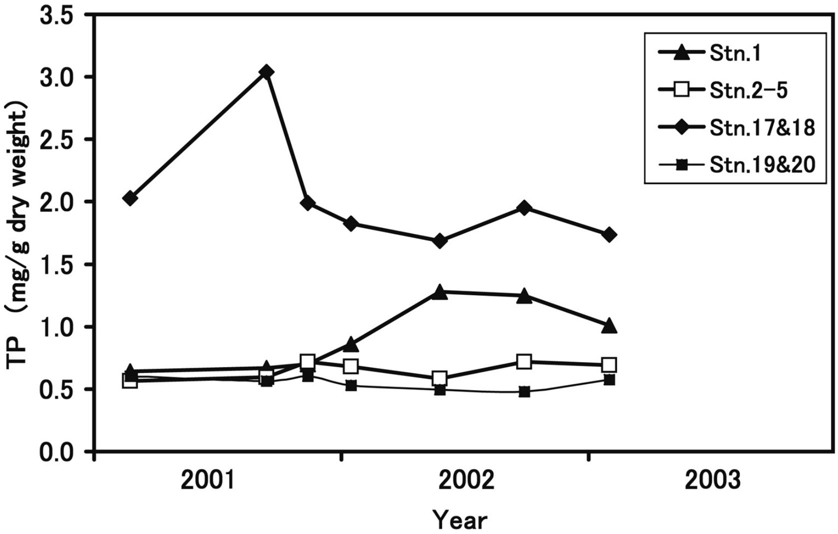

Fig. 7. Change of TP concentrations in sediment from February 2001 to February 2003

▲ : Stn. 1 (Center of new fish farming site)

□ : Average of Stns. 2-5 (Edges of new fish farming site)

◆ : Average of Stns. 17 and 18 (Former fish farming site)

■ : Average of Stns. 19 and 20 (Pearl oyster farming site)

Discussion

It is necessary to keep balance between organic matter lord and it's decomposition for sustainable production of aquaculture. So, the environment of fish farming site should be monitored with appropriate method. Until now, many indicators were proposed to evaluate the impact of aquaculture on the environment (Yokoyama, 2000). Among them, AVS-S is one of the most common parameter, used to many investigations in Japan, from it's easiness to measure and unnecessary expensive tools (ex. Tsutsumi and Inoue, 1995; Pawar *et al.,* 2001; Yokoyama, 2002 etc.). On the other hand, most of these investigations were carried out in the old fish farming sites established many years ago, there was not so much examples of investigations of AVS-S against to increasing of organic matter lord by establishment of new fish farming site. And it was insufficient to clarify quantitative relationship between organic matter lord and change of benthic environment. So, it was expected to establish the method to control benthic environment in and around fish farming sites, by examination of AVS-S and organic matter lord in 2001.

The shift of fish farming cages to the new fish farming site was carried out from May to November 2001. AVS-S in the new site were very low before the shift of fish farming cages, but AVS-S drastically increased at the same time with the start of shift of cages to the new site. This rise of AVS-S in the new site suggest increase of organic matter lord with the shift of cages. Usually in this investigation area, fish seeds for aquaculture were introduced in Spring and begun to take from the next Autumn. In the new site, it seems that organic matter lord increased due to shift of fish cages, rise of feed consumption with growth and high water temperature more than 19.6℃ from May to September in 2001. Artificial organic matter lord to the new site increased from 0 to the level shown in Fig. 3 in November in 2001, when cage's shift was completed. It was obviously that AVS-S increased consistently with increasing feeds used from April to November. This result indicates that AVS-S of sediment is one of the most appropriate indicators.

On the other hand, rise of AVS-S were recognized at the edge of the new fish farming site but at the stations from the edge more than 50m, the rise was slight. It was indicated that the effect to benthic environment from fish farming cages was limited within 50m from the cages (Kubota, 1977). This agree with the investigation of the new fish farm site of Shitaba bay.

Before this investigation, it was expected that the sediment AVS-S would decrease in the old site after the shift. The effect of shift of fish cages on the benthic environment has not been found yet. As mentioned above, the effect from the new fish farming site was limited within about 50 m. In this investigation, the stations in the old fish farming site were situated just under the fish cages, it was thought that there was not major change of organic matter lord from cages. For the estimation of removal of fish cages from inside the bay, it is needed to continue the investigations added other stations far from fish cages more than 50 m.

Not only AVS-S but also TOC, TN and TP contents are often used for the indicators of benthic environment. There were not large difference about TOC and TN contents in the sediment between the new and the old fish farming sites. But, only TP content in sediment among these three parameters was always 2 times higher in the old site than that of the new site in this investigation. Though, the amounts of the feeds consumed in the new and the old sites were nearly equal in 2002.

To clarify the reason for this difference, the settling flux of particulate was measured, near the bottom in the new, old and pearl oyster farming site. TP content in the settling flux was higher in the both fish farm sites than that of the pearl oyster farm site. But TP content in the settling flux in the new site was higher than in the old site, except for one month. This result show that though the sediment TP in the old site was quit high compare to the other sites, the settling flux of TP in the new and old sites are almost equal or higher in the new site.

The main material of fish feeds is fish meal, including large amount of phosphorus derived from fish bones (Satoh, 2003). Decomposition of phosphorus derived from fish bone would occur slowly, so they would remain in the sediment for a long time. Most of it is the poor solubility (Satoh, 2003), and the possibility of the storage to the sediment has been indicated. So, it was estimated that the TP concentration of sediment will keep increasing in the new fish farming site during the fish culture was continued.

AVS-S in sediment is an appropriate indicator for monitoring the quick response of the benthic environment to the organic matter lords from fish farming. The response of the sediment TP concentration to the influent from fish farm is quite slow compared to AVS-S. So, TP in sediment is an appropriate indicator of long time influent from fish farming.

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Assimilative capacity of fish farm environments as determined by the benthic oxygen uptake rate: Studies using a numerical model

Katsuyuki ABO * and Hisashi YOKOYAMA *

Abstract : In order to promote improvements in the environmental quality of aquaculture grounds, the Japanese government enacted the "Law to Ensure Sustainable Aquaculture Production" in 1999. In the Basic Guidelines for this law, an environmental criterion based on the benthic oxygen uptake (BOU) rate was adopted to assess the quality of aquaculture environments. Biological mineralization is considered to peak when the BOU rate reaches its maximum, which is an indicator of the maximum desirable level of organic matter loading. The acid volatile sulfide (AVS-S) content of the sediment increases in direct correlation to the organic matter loading, and is used as an indicator of the assimilative capacity of bottom sediments. The AVS-S value corresponding to organic matter loading when the BOU rate is at its maximum is defined as the standard value. Recent studies, however, have suggested that it is difficult to detect the maximum (peak) BOU and to determine the standard value through in situ investigations. The practical applicability of this criterion therefore needs to be re-examined scientifically. To do this, we developed a three-dimensional numerical model that takes into account advection, dispersion, sedimentation, and decomposition of organic matter from fish farming systems. The numerical model should be used instead of in situ investigations for the practical application of the criterion. We also used this model to assess the assimilative capacity of an existing fish farm on the basis of the criterion. The model proved to be an effective tool for evaluating the assimilative capacity of the environment of fish farms.

Keywords: environmental criteria, fish farm, numerical simulation, Law to Ensure Sustainable Aquaculture Production

Introduction

Supported by the development of production techniques and by economic growth, Japan has succeeded in increasing its aquaculture production, while the total amount of fishery products has been decreasing for the last 10 consecutive years. Aquaculture, however, has had a large impact on the environment. In particular, overstocking of aquaculture pens has caused environmental deterioration such as eutrophication, hypoxia, and occurrences of noxious red tide.

The Japanese government enacted the "Law to Ensure Sustainable Aquaculture Production" in 1999 in order to promote improvements in the environmental quality of aquaculture grounds. In the so-called Basic Guidelines for this law, environmental criteria and indicators were adopted to identify healthy farms and "critical" farms (those not being managed sustainably). These criteria and indicators should now be revised, however, on the basis of more recent data (Yokoyama, 2003). Specifically, sediment sulfide content, which was adopted as an indicator of the benthic oxygen uptake (BOU) rate, is difficult to apply (Yokoyama, 2000; Yokoyama and Sakami, 2002). The practical applicability of this criterion needs to be re-examined. We therefore developed a numerical model to examine the practical application of the criterion and studied the

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assimilative capacity of fish farms.

Environmental impact of fish farms

Fish farms discharge large amounts of organic matter into the environment. Comparison of the ratio of the distribution of feed to wastage, fish growth, and excretion and feces shows consistently high discharge rates for different species and feed types and varying assessment measures (Table 1). Based on an assessment of nitrogen content, it has been estimated that 80% of the feed inputs to fish farms is discharged out of the culture cages: 20% in the form of feed wastage, and 60% in the form of fish excretion and feces production (Itoh, 1994). On the basis of protein content, Yamaguchi (1978) estimated the ratio in fish farms that rear red sea breams. He estimated that 20% of the feed is discharged into the environment directly as feed wastage and that 60% of the feed is discharged as excretion and feces. Watanabe (1991) studied the distribution of feed in fish farms that rear yellowtails based on dry matter content. He showed that in fish farms that feed moist pellets a total of 74% of the feed is discharged into the environment, 19% as feed wastage and 55% as excretion and feces, while in fish farms that use raw fish, 85% of the feed is discharged, with feed wastage accounting for 72% and excretion and feces for 13%. Bergheim et al. (1991) estimated that in salmonid farms that feed dry pellets, 75% of the feed is discharged: 10% as feed wastage and 65% as excretion and feces. According to Wu (1995), eventually some 80-84% C, 52-95% N, and 82% P in the feed may be lost to the environment in a salmonid farm using artificial feed.

The Law to Ensure Sustainable Aquaculture Production

To improve the environmental quality of aquaculture grounds and maintain suitable conditions for stable aquaculture production, the Law to Ensure Sustainable Aquaculture Production (hereinafter referred to as the Law) was enacted in 1999. As a fundamental guide for putting the Law into practice, the Minister of Agriculture, Forestry, and Fisheries produced the "Basic Guidelines to Ensure Sustainable Aquaculture Production", which detailed matters relevant to the goal of improving aquacultural practices. The Law stipulates that fisheries cooperative associations should enact an "Aquaculture Ground Improvement Program" so as to ensure sustainable aquaculture, and also secure the approval of the prefectural governor. The Basic Guidelines contain environmental criteria to measure the environmental condition of aquaculture grounds. The criteria utilize three indicators: the dissolved oxygen content of the water within fish cages, the condition of macrofauna beneath the fish cages, and the sulfide content (acid volatile sulfide, AVS-S) of the sediment beneath the cages (Table 2). The criteria serve to identify healthy and critical farms; farm environments are identified as healthy or critical based on the values measured for these indicators, relative to established thresholds.

Dissolved oxygen is an important factor for

Table 1. Comparison of the ratios of the distribution of feed to wastage, fish growth, and excretion and feces in fish farms, for different species and feed types and varying assessment methods.

	Seabreams	Yellowtails	Yellowtails	Salmonids
Feed	100	100	100	100
Feed Wastage	20	19	72	10
Excretion and Feces	60	55	13	65
Growth of Fish	20	26	15	25
	Yamaguchi (1978) Raw Fish Protein Basis	Watanabe (1991) Moist Pellets Dry Matter Basis	Watanabe (1991) Raw Fish Dry Matter Basis	Beregheim (1991) Dry Pellets Nitrogen Basis

Table 2. Environmental criteria adopted in the Basic Guidelines for the Law to Ensure Sustainable Aquaculture Production.

Item	Indicator	Criteria for healthy farms	Criteria for critical farms
Water in cages	Dissolved oxygen	> 4.0 ml/l	< 2.5 ml/l
Bottom environment	Sulfide (AVS-S)	Less than the value at the point where the benthic oxygen uptake rate is maximum	> 2.5 mg/g dry sediment
	Benthos	Occurrence of macrobenthos throughout the year	Azoic conditions for more than 6 months

maintaining the life of cultured organisms. The criteria established 4.0 ml/L and 2.5 ml/L of dissolved oxygen as thresholds for identifying healthy and critical farms, respectively. Macrofauna have often been used as a sensitive indicator to assess fish farms environments (Yokoyama, 2002). The criteria used in the Basic Guidelines only specify that the benthos beneath the culture cages should be alive. The farm environments are identified as healthy when macrobenthos occur throughout the year, and they are identified as critical when azoic conditions occur for more than 6 months in a year. Sulfide content (AVS-S) levels are used as an indicator of the assimilative capacity of bottom sediments. The threshold AVS-S level for healthy farms is determined by reference to the BOU rate; the threshold for critical farms is > 2.5 mg/g dry sediment. Using a simple numerical model, Omori et al. (1994) found a peak in the BOU rate which they took to be an indicator of the level of organic matter loading that would result in the maximum rate of re-mineralization. Takeoka and Omori (1996) proposed a method to determine the assimilative capacity of fish farm environments by using the sulfide content as an indicator, because sulfide content is positively correlated with organic matter loading. In the criteria, farm environments are identified as healthy when AVS-S is less than the AVS-S value at the point where the BOU rate is maximized. The concept of using sulfide content as an indicator to identify healthy farms is unique, but there are problems in its practical application, as described below. In the following section, we examine the practical use of the indicator of sulfide content to identify healthy farms.

Assimilative capacity based on benthic oxygen uptake rate

The use of sulfide content as an indicator considers the capacity of bottom sediments to assimilate organic wastes, and it is based on the relationship between the organic matter loading and the BOU rate in the bottom water. An increase in the organic matter loading to the sea bottom is accompanied by an increase in the aerobic degradation of organic matter in the sediment. Increases in organic matter loading also lead to a decrease in dissolved oxygen content, however, causing benthic conditions to become anaerobic, at which point the BOU rate begins to decrease. Consequently, organic matter loading should be limited to the level at which the BOU rate is at its maximum, because this corresponds to the point at which the greatest biological re-mineralization of organic matter takes place (Fig. 1). There is a positive correlation between the organic matter loading and sulfide content in the sediment, and thus the AVS-S level that corresponds to the BOU maximum is used as an indicator of the assimilative capacity of fish farms, and to determine which are healthy.

There are problems in applying this criterion to existing aquaculture farms. Recent studies have suggested that it is difficult to detect the maximum (peak) BOU and to determine the standard AVS-S value through in situ investigations (Yokoyama and Sakami, 2002; Yokoyama, 2003; Abo and Yokoyama, 2003). In order to determine the standard AVS-S value of the criterion, it is necessary to detect

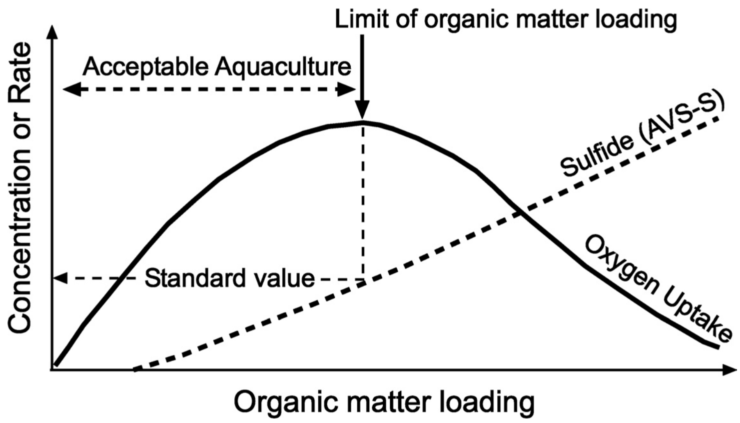

Fig. 1. Acceptable limits for organic matter loading from fish farms, and the relationship to benthic oxygen uptake and sediment sulfide content (adapted from Takeoka and Omori, 1996).

the maximum value of the BOU rate relative to the organic matter loading rate from a farm. Theoretically, we have to investigate the BOU rate when the level of organic matter loading is changed, but this is almost impossible to do in an existing farm. In addition, it takes many years to investigate, even if the organic matter loading is altered. Consequently, it is almost impossible to determine the standard BOU value by this method. Another method involves investigating the BOU rate in several farming areas whose topography and hydrodynamic conditions are very similar, and detecting the maximum among the similar farming areas. Many researchers have carried out these in situ investigations in Japan; however, they were unable to detect the maximum because BOU rates are very sensitive to changes in oxygen supply, induced by water exchange. It is also impossible to select a sufficient number of farming areas whose topography and hydrodynamic conditions are similar enough to enable detection of the maximum. Moreover, some researchers intend to detect the maximum by measuring BOU rates at many points in one fishing area. This approach is unsound, however, because the BOU rate depends largely on oxygen flux, which varies significantly within a short distance in a farming area (Abo and Yokoyama, 2003).

These problems suggest that we cannot determine the standard value through in situ investigations. It is possible, however to utilize a numerical model to determine the standard value. By using a numerical model, we can simulate benthic quality when the organic matter loading rate is changed in a farm. The BOU rate can then be calculated as a function of variations in the organic matter loading rate, and the maximum and standard values for sulfide content estimated.

Numerical model

The numerical model to estimate the maximum BOU rate and determine the standard AVS-S value defined in the criteria used in the Basic Guidelines for the Law deals with three spatial dimensions, and considers advection, dispersion, sedimentation, and degradation of organic matter loading from fish farms (Fig. 2). We first calculate water movements using a multi-level density "primitive" flow model. The flow model divides the area into meshes, and solves the fundamental equations obtained by integrating the equations within the meshes. Secondly, we calculate advection and diffusion of dissolved oxygen, and advection and diffusion of organic matter loadings from fish farms, including their sedimentation (Fig. 2b). We also calculate the aerobic and anaerobic degradation of the organic matter. In this model we express the flow of organic matter very simply (Fig. 2c). Organic matter loading from fish farms sinks at some sedimentation rate, and organic matter in the water column degrades

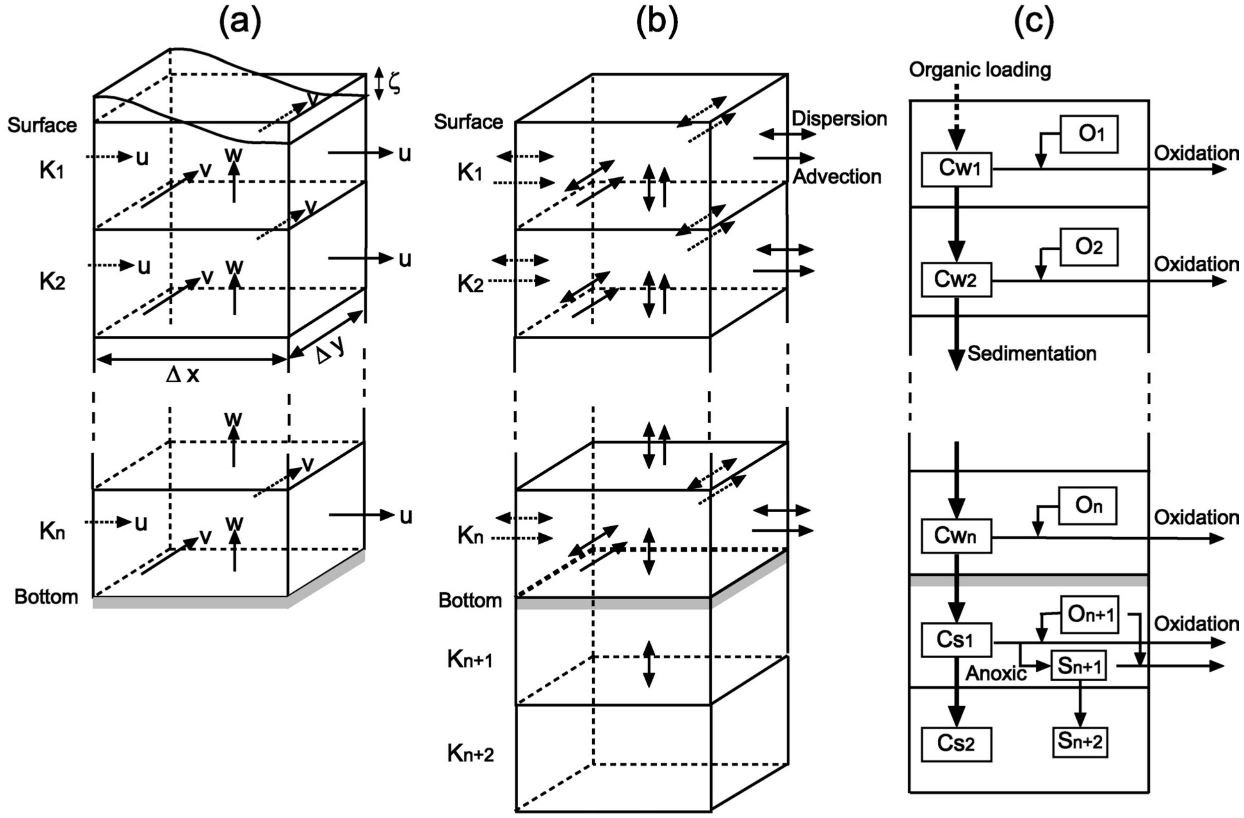

Fig. 2. Schematic views of the three-dimensional numerical model. (a) Multi-level stratified flow model. (b) Advection and diffusion of organic matter and dissolved oxygen. (c) Flow chart of the sedimentation, oxidation and anoxic decomposition of organic matter.

aerobically. Once organic matter accumulates on the bottom, it degrades both aerobically and anaerobically. Reduced substances derived from anaerobic degradation of organic matter consume oxygen through chemical oxidation.

The relational equations and parameters used were according to Omori et al. (1994). Using this model, we calculated approximate stationary solutions under the given conditions.

Assessment of the assimilative capacity of aquaculture environment in Gokasho Bay

We examined application of the numerical model to assess the existing aquaculture environment in Gokasho Bay. Gokasho Bay is located on the southern coast of central Japan facing the Pacific Ocean (Fig. 3). This bay is a typical semi-enclosed estuary consisting of three branches: the main inlet, the Hasama-ura inlet, and a third branch. Fish farms are concentrated in Hasama-ura inlet. In this bay aquaculture is prosperous and about 1000 metric tons of fish are produced annually. We divided the Gokasho Bay area into meshes of 100 m^2 and 5 m depth, and identified some meshes as fish farming sites (Fig. 4). Organic matter is assumed to be loaded into the surface layers from fish farming site meshes. With this geometry, we simulated changes in the BOU rate relative to the organic matter loading rate from the fish farming sites.

First, we calculated movement of organic matter loaded from fish farming sites when the organic matter loading rate was equal to the real value for the existing farms in Gokasho Bay. The organic matter content of the sediment and the BOU rate were compared for Gokasho Bay (Fig. 5), with a unit of organic matter content given as an oxygen equivalent (μ molO_2/cm^3). Organic matter from fish farms accumulated mainly on the sea bottom near the fish farming sites. The BOU rate was high near the shore of Hasama-ura inlet because of the large oxygen supply at the sea surface; the dissolved oxygen concentration in the bottom water of the shallow area was consequently high. Other than in the shallow area, the BOU rate was high at the outer side of the fish farming area (at the mouth of Hasama-ura inlet), where there was high organic matter loading and a large supply of oxygen. The BOU rate was low at the inner side of the fish farming area, where the oxygen supply was very small due to oxygen depletion.

Next, we simulated the BOU rate when the organic matter loading was changed, in order to estimate the maximum BOU rate at each fish farming site (Fig. 6). The organic matter loading rate was represented as a unit of oxygen equivalent of feed fed per day (μ molO_2/cm^2/day), and the organic matter loading rate to the sea surface was assumed to be the same at each farming site. At farming site 1, the BOU rate varied relative to the organic matter loading rate, with the maximum BOU rate occurring when the organic matter loading rate was 3 μ molO_2/cm^2/day. This value was an allowable organic matter loading rate maximum for farming site 1, with the aquaculture environment of farming site 1 regarded as healthy when the organic matter loading rate was within 3 μ molO_2/cm^2/day. In farming sites 5, 7, and 11, the BOU rate reached its maximum when the organic loading rate was 10, 25, and 95 μ molO_2/cm^2/day, respectively; these values were taken as the allowable organic matter loading rate maximums for each farming site. These values are plotted and contour lines drawn showing the organic matter loading rate limits in Gokasho Bay (Fig. 7). The values are high at the mouth of the Hasama-ura inlet and very low at the innermost part of the inlet. The limit values increase sharply towards the mouth of the inlet. As the actual organic

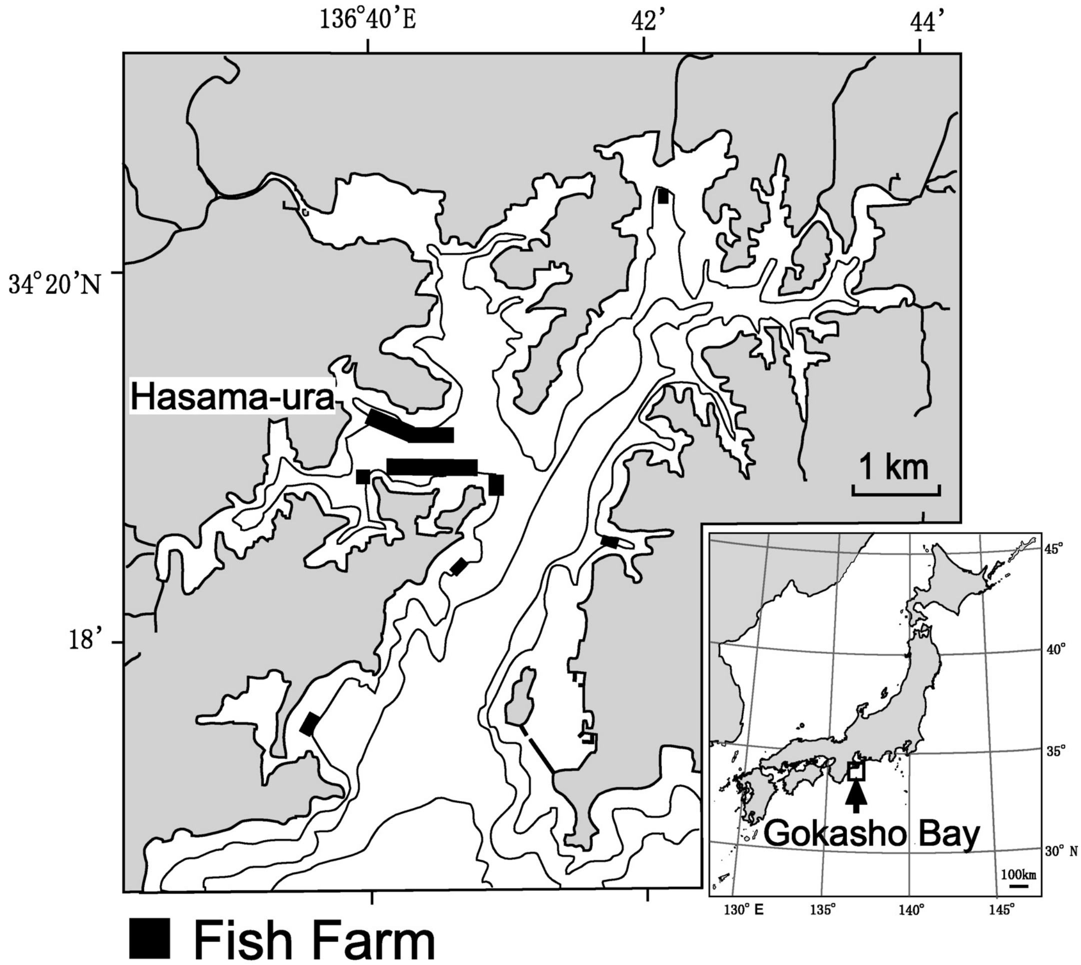

Fig. 3. Map of Gokasho Bay. Solid areas denote fish farming sites.

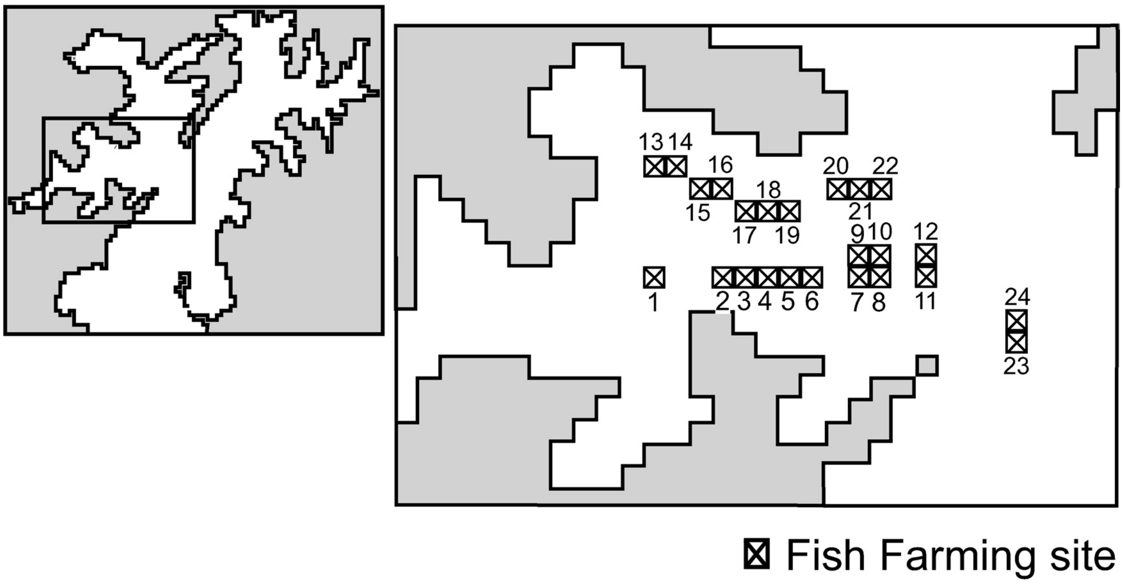

Fig. 4. The model geometry of Gokasho Bay. Squares with crosses indicate fish farming sites 1-24.

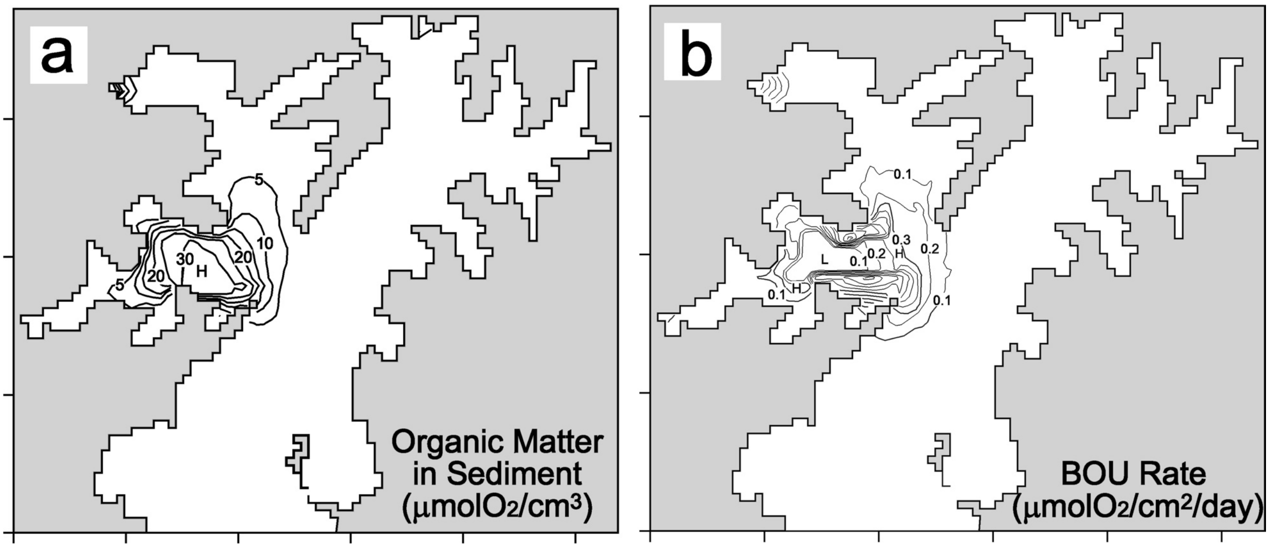

Fig. 5. Distribution of organic matter content in (a) sediment and (b) benthic oxygen uptake rate, calculated by the numerical model.

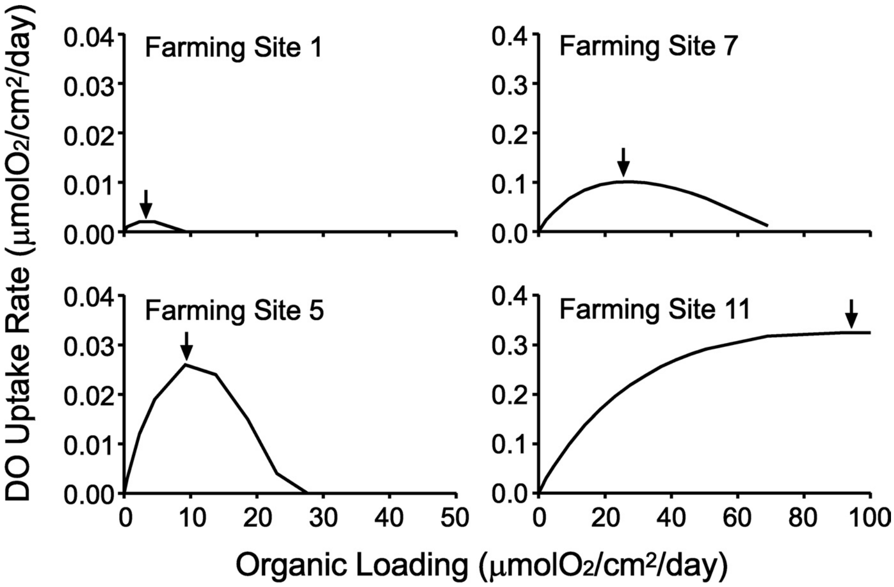

Fig. 6. The relationships between the benthic oxygen uptake rate and organic matter loading rate at fish farming sites 1, 5, 7, and 11 (see Fig. 4), as calculated by the numerical model.

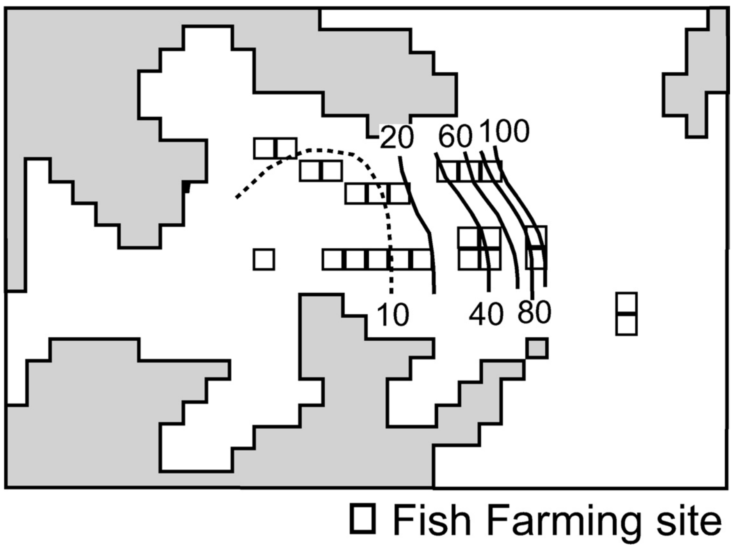

Fig. 7. Isopleths of the limit values of the organic matter loading rate (μ molO_2/cm^2/day) in Gokasho Bay, estimated by the numerical model.

matter loading rate in each mesh of the farming sites is estimated at about 20 $\mu molO_2/cm^2/day$, there is sufficient capacity for aquaculture at the mouth of the inlet. However, the capacity is very small at the inner part of the inlet, where it is one-tenth of the capacity at the inlet mouth.

Conclusion

The numerical model is an effective tool for assessing the limit of organic matter loading from fish farms for ensuring healthy aquaculture environments, on the basis of the environmental criterion adopted in the Basic Guidelines for the Law to Ensure Sustainable Aquaculture Production. Before the model can be practically applied to determine the standard sulfide value of the criterion, the model needs to be reexamined and the parameters defining the aquaculture ecosystem refined. We will also attempt to carry out an in situ investigation of the benthic quality of a fish farming area to refine the model for practical application.

To improve aquaculture environments with the goal of sustainable aquaculture production, we should ensure that production levels are within an area's capacity; infection caused by overstocking can be addressed through reduction in production or rearrangement of aquaculture pens within an aquaculture area. The model can serve as an effective tool for suggesting appropriate spatiotemporal use of aquaculture grounds.

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Macrobenthos, current velocity and topographic factors as indicators to assess the assimilative capacity of fish farms: Proposal of two indices

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Abstract In order to provide site selection guidelines for fish farming, two indices have been previously proposed based on surveys of the macrobenthos and bottom environments conducted at fish farms in Kumano-nada, central Japan. In this review, these results are summarized, and requisites for determining the limit of maximum fish production are discussed from a standpoint of assimilative capacity of fish-farm environments. An index 'ED' (Embayment Degree) is calculated from the distance from a bay mouth to a fish-farm site, the width of the bay, the water depth of the site and the maximum depth at the bay mouth. Another index, 'ISL' (Index of Suitable Location) is calculated from the water depth and current velocity under a fish cage. Current velocities can be estimated by plaster balls readily and simultaneously at many stations. Biotic and abiotic factors at the fish farms were found to be changed along gradients of fish production and ED or ISL, suggesting that these indices are effective for estimating the assimilative capacity. ED can be used as a simple indicator for the site selection. ISL has a wider potential application to assess the assimilative capacity under a variety of topographical conditions.

KEY WORDS: Fish farm, Assimilative capacity, Current velocity, Environmental criteria, Plaster ball

Introduction

Intensive net-pen fish farming generates large amounts of uneaten food and fish feces. These particulate organic wastes generally settle on the seabed near to the cages. When the accumulation of wastes exceeds the assimilative capacity of the water body, negative effects on the benthic ecosystem such as impoverished infauna and outgassing of hydrogen sulfide often occur (reviewed by Gowen *et al*., 1991; Pearson and Black, 2001). To maintain sustainable aquaculture, it is necessary to assess farm environments objectively, and to conduct cultivation within the range of the assimilative capacity, which is defined as the ability of an area to maintain a "healthy" environment and "accommodate" wastes (Fernandes *et al*., 2001).

The macrobenthos community has often been used as a sensitive indicator for environmental monitoring of organically polluted areas (reviewed by Pearson and Rosenberg, 1978). Assessments of fish-farm environments using the macrobenthos have also been conducted in many countries of the world. These studies have shown that a reduction in species richness and/or species diversity; a decrease in the number of large-sized species; the disappearance of echinoderms; and the appearance of dense populations of the opportunistic polychaete Capitella species (especially species I), which often result in an increase in the total macrofaunal abundance, are typical effects of mariculture farming on the macrobenthos (reviewed by Gowen *et al*., 1991; Pearson and Black, 2001).

In Japan, the "Law to Ensure Sustainable Aquaculture Production" (hereinafter referred

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to as "the Law") was established in 1999 to promote the improvement of aquaculture grounds. Based on the Law, environmental criteria for indicating practical goals for the improvement of aquacultural environments were established. In one of these criteria, the macrobenthos was used as a bio-indicator for identifying healthy and critical environments of mariculture farms. This criterion, however, only specifies that the macrobenthos should be alive. A healthy environment is identified in terms of the existence of live macrofauna throughout the year, while a critical environment is identified from azoic conditions during half a year or more. This criterion has limited ecological relevance, however it was pushed through as the criterion is considered convenient in terms of the ease of monitoring by farmers themselves. For the future, a more detailed criterion should be established based on scientific data.

Under aerobic conditions, organic wastes from aquaculture are liable to be incorporated by benthic animals directly or indirectly through the microbial food chain. Increased benthic animals accelerate the oxygenation process of the sediment by their bioturbation activities. Benthic animals may be fed on by predators, resulting in increase of consumer populations in higher trophic levels.

The remineralization of loaded organic wastes by benthic animals begins originally from supply of oxygen, which is controlled by the water flow and/or water exchange between the fish-farm grounds and the surrounding water. Increased current velocities not only increase the oxygen supply (Jørgensen and Revsbech, 1985; Findlay and Watling, 1997) but also reduce the loading of particulate organic wastes per unit area of the seabed due to waste dispersion (Gowen and Bradbury, 1987; Chamberlain *et al*., 2001). Lumb (1989) demonstrated the importance of avoiding sites with low water movement for reducing the risk of environmental deterioration. Water depth under fish cages also potentially has a great effect on the waste dispersion (Gowen and Bradbury, 1987; Hevia *et al*., 1996).

As the assimilative capacity is different from farm to farm depending on the physical components such as the topography and the current velocity, the maximum limit of fish production should be determined for each individual farm. From this point of view, the Law determined another environmental criterion as "acid-volatile sulfide (AVS) should be less than the maximum value of benthic oxygen uptake (BOU) at each fish farm". However, it is difficult to specify the maximum BOU value from the field survey (see Abo and Yokoyama, 2006 in this volume).

In order to assess the assimilative capacity of fish-farm environments, and to provide site selection guidelines, surveys of the bottom environments and macrobenthos were conducted in fish farms in Kumano-nada, Pacific coast of central Japan (Yokoyama *et al*. 2002a, b, 2004). In this review, these results are summarized, and requisites for determining the limit of the maximum fish production are discussed from a standpoint of the assimilative capacity.

Index incorporating topographic factors

Yokoyama *et al*. (2002a, b) conducted a quantitative survey of the macrobenthos in August and September 1998 at 22 fish farms distributed in ten small bays along the coast of Kumano-nada, central Japan, in order to assess the environmental impacts of fish-farm wastes under a variety of topographic conditions and to suggest site selection guidelines for sustainable fish farms. In this area, fish farming has developed steadily since the introduction of yellowtail (*Seriola quinqueradiata*) culture in the early 1960's. Since the middle of the 1970's, a total of 15,000–20,000 metric tons of fish has been annually produced mainly of red sea bream (*Pagrus major*) and yellowtail. In 1998, annual fish production of each farm in this area ranged from 61 to 1,507 metric tons (Tokai Regional Agricultural Administration Office, 1999).

Yokoyama *et al*. (2002a) devised an index "ED" (Embayment Degree) of the topographic situation of a sampling site. When a fish farm is located in a secondary bay whose axis crosses the axis of the main bay at an angle of <90° (Fig. 1), ED is expressed by ED = $(L_1/W_1+L_2/W_2)(a/Ds)(b/Dm)$, where L_1 is the distance from the mouth of the main bay to the mouth of the secondary bay, L_2 is the distance from the mouth of the secondary bay to the

Fig. 1. Parameters for the calculation of ED (after Yokoyama *et al.,* 2002a).

fish-farm site, W_1 is the width of the main bay, W_2 is the width of the secondary bay, *Ds* is the water depth at a sampling site or, if present, the depth of any sill which exists between the site and the bay mouth, *Dm* is the maximum depth at the bay mouth, *a* is the mean depth of all the sampling sites, and *b* is the mean depth of the bay mouths in the study area. Yokoyama *et al.* (2002a) adopted $a = 20$, and $b = 45$ in their case study conducted in Kumano-nada. When a fish farm is located in a secondary bay whose axis crosses the axis of the main bay at an angle of >90°, ED is expressed simply by $ED = (L/W)(a/Ds)(b/Dm)$, where L is the distance from the mouth of the main bay to the fish-farm site, and W is the width of the main bay.

Environmental deterioration does not occur in the deeper offshore areas in Kumano-nada with ED values <2, even if a high production (>1,000 t/yr) of fish is maintained. In fact, within the deeper offshore areas, DO (dissolved oxygen) was usually more than 5 mg/l, and AVS (acid-volatile sulfide) was usually less than 0.6 mg S/g, even for medium- and large-scale farms (fish production, >500 t/yr). Such an undisturbed condition and an enhanced food supply from the fish cages resulted in large macrofaunal biomasses, high densities and high species richness, which were generally encountered >10 g/m^2, >2,000 individuals/m^2 and >30 species/0.04 m^2, respectively. On the other hand, deterioration of the sediment quality (AVS, >1 mg S/g dry), deoxygenation of the bottom water (DO, <2 mg/l) and decreases in biomass (<1 g/m^2), density (<500 individuals/m^2) and species richness (<5 species/0.04m^2) were often found in the inner and shallower parts of the bay (ED, >5). This tendency was more conspicuous in large-scale farms (fish production, >1,000 t/yr) than in small-scale farms (<500 t/yr). These findings suggest that variability of the macrobenthos and environmental factors are attributable to the topography as well as to the aquacultural activities, and that topography is the important factor in the location of environmentally efficient fish farms.

Yokoyama *et al.* (2002b) also examined the species composition of the macrobenthos as an indicator of fish farm environments. They found six assemblages (A–F) in August–September 1998 at the fish farms in Kumano-nada by the cluster analysis. These assemblages could be classified into three groups, i.e., a group characteristic of a healthy zone (A–D), a group characteristic of a cautionary zone (E), and an azoic group characteristic of a critical zone (F), based on the macrofauna and chemical factors of the bottom water and the sediment. These assemblages were placed in a gradient of ED versus fish production (Fig. 2). Fig. 2 suggests that all levels of fish production (<1,500 t/yr) could be sustained in areas where ED is <3

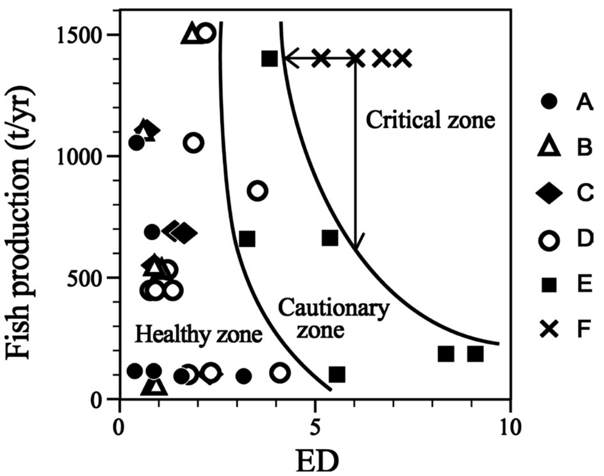

Fig. 2. Distribution of the six assemblages (A–F) in a gradient of ED versus fish production (after Yokoyama et al., 2002b).

and smallest-scale fish production (<200 t/yr) could possibly be conducted in areas where ED is <10, but medium- and large-scale production should be limited to areas where ED is <5. A fish farm with large-scale production (e.g., 1,400 t/yr) and located in the critical zone (e.g., ED = 6) should be shifted to an area with ED values <4 or annual production should be reduced to <600 t to alleviate the critical conditions.

Many mathematical models have been developed to predict benthic impacts and responses to organic enrichment associated with fish farming (reviewed by Henderson *et al.*, 2001). Most of them recognized that the current flow is a key factor in predicting the dispersion and input of organic wastes to the seabed (e.g. Hevia *et al.*, 1996; Findlay and Watling, 1997). ED is an index based on the same concept as those adopted in the previous modeling studies, which demonstrated that dispersive environments are less susceptible to environmental degradation than semi-enclosed systems, but a novel aspect is that the index is readily applicable for use in decisions about the siting of fish farms. Factors such as the inflow of freshwater into the bay, the current outside the bay, and wind velocity and direction, which may vary in different localities might also control flushing. In neighboring localities under similar oceanographic conditions, however, benthic impacts from fish farming might depend largely on the topographic conditions. Results obtained from these surveys demonstrated the importance of topographic factors for assessing the impact of organic wastes and for developing site selection guidelines.

Index incorporating the current velocity and water depth

ED is an index based on topographic factors only, and has proved helpful to develop guidelines for siting fish farms within the Kumano-nada area, however, it is unknown whether this index is applicable to other localities exhibiting different tidal ranges or different bay sizes. The current flow and water depth are the most important factors that control directly the waste dispersal and loading. These factors are essential to assess the assimilative capacity of fish-farm environments.

Yokoyama *et al.* (2004) conducted a survey of the water flow to examine whether the current velocity and water depth in fish farms can be used as indicators for site selection guidelines. They proved that plaster balls (plaster of Paris : water = 100 g : 70 ml) can be used as a convenient and effective tool for measuring the time-averaged current velocity. They revised the method for the calculation of the time-averaged intensity of water motion that was presented by Komatsu and Kawai (1992) and Komatsu (1992). Yokoyama *et al.* (2004) showed the equation,

$$v = \frac{\left(\sqrt{W_0 - W_S} - \sqrt{W - W_S}\right)(284 - 4.03T)}{h} - 0.048T - 0.27$$

where v is the time averaged current velocity (cm/s), W_0 is the wet weight (g) of a plaster ball including an iron bolt before setting on the seabed, W is the wet weight (g) of the plaster ball including the iron bolt after being retrieved from the seabed, Ws is the weight (g) of the iron bolt, T is the average water temperature (℃) during the immersion period, and h is the immersion period

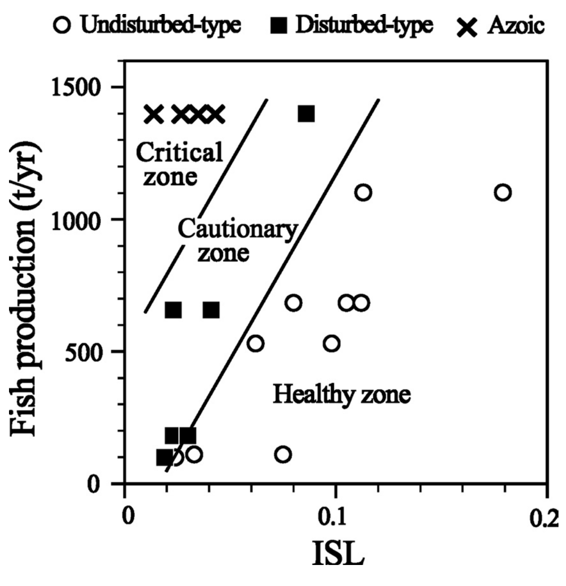

Fig. 3. Distribution of the three assemblage groups in a gradient of ISL versus fish production (adapted from Yokoyama *et al.*, 2004). Symbols represent the group characteristic of the healthy zone (○), the group characteristic of the cautionary zone (■), and the group characteristic of the critical zone (×), respectively.

(hours). Plaster balls (diameter = 48 mm), which were fixed on a stand using a bolt and nuts, were put 1.0 m above the seabed at 20 stations in 8 fish farms in Gokasho Bay and Owase Bay for about 50 hours at the same time during neap- and spring-tide periods in September 2003.

Yokoyama *et al.* (2004) devised an index 'ISL' (Index of Suitable Location). ISL is expressed as ISL = DV^2, where D is the water depth (m) at a fish-farm site and V is the time-averaged current velocity (m/s). The mathematical derivation of the index is as follows: the loading rate of organic wastes to the seabed has an inverse relationship to DV; as the current velocity maintains the oxygen supply that serves to remineralize the loaded organic wastes, the value obtained by multiplying DV by V, i.e., DV^2 will represent the assimilative capacity of the water body.

Three zones of fish-farm environments, i.e., healthy, cautionary and critical zones, which had been defined on the basis of the macrofauna and chemical factors (Yokoyama *et al.*, 2002b), were also arranged in a grid of ISL versus fish production (Fig. 3). The healthy zone was located at areas having large ISL values, whereas the critical zone was located at areas having small ISL values and high levels of fish production.

Field data on biotic and abiotic factors that have been obtained from the same stations (Yokoyama *et al.*, 2002a) were used to validate ISL (Fig. 4). Values

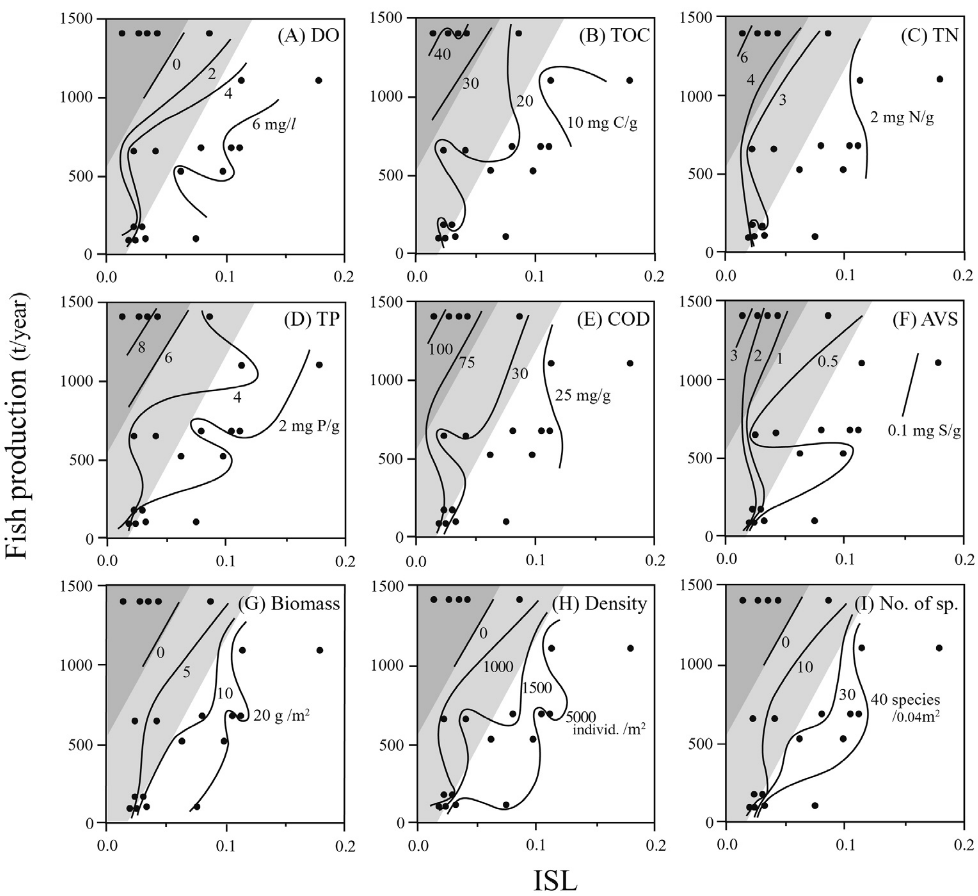

Fig. 4. Distribution of values of six abiotic (A–F) and three biotic (G–I) factors in a gradient of ISL versus fish production (after Yokoyama *et al.*, 2004). Dark, gray, and white areas show critical, cautionary, and healthy zones, respectively (defined in Fig. 3). (A) Dissolved oxygen of the bottom water, (B) total organic carbon in the sediment, (C) total nitrogen in the sediment, (D) total phosphorus in the sediment, (E) chemical oxygen demand of the sediment, (F) acid-volatile sulfides in the sediment, (G) biomass of the macrobenthos, (H) density of the macrobenthos, and (I) number of species of the macrobenthos.

Table 1. Values of benthic components for identifying cautionary and critical conditions of fish-farm environments (adapted from Yokoyama *et al.* 2004)

Benthic components	Cautionary condition	Critical condition
Sediment		
Total organic carbon (mg C/g dry)	20 – 30	> 30
Total nitrogen (mg N/g dry)	2.5 – 4.0	> 4.0
Total phosphorus (mg P/g dry)	4 – 6	> 6
Chemical oxygen demand (mg/g dry)	30 – 75	> 75
Acid-volatile sulfide (mg S/g dry)	0.5 – 1.5	> 1.5
Macrobenthos		
Biomass * (g/m^2)	< 10	0
Density (individuals/m^2)	< 1500	0
Number of species (/0.04 m^2)	< 20	0

* Wet weight of animals excluding the shell of mollusks.

of biotic and abiotic factors changed along a gradient of ISL versus annual fish production. As ISL values decreased and fish-production levels increased, values of DO of the bottom water decreased, values of sediment total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and AVS increased, and values of biomass, density and number of species of the macrobenthos decreased. These findings suggest that environmental conditions are predictable in gradients of ISL and fish production, and that ISL is an effective indicator in the assessments of the assimilative capacity and the upper limit of fish production. For instance, at farms showing ISL of 0.05, it is recommended to restrict fish production within 500 t/yr, while at farms having ISL of 0.1, allowable production may increase to 1,000 t/yr (Fig. 3).

Since benthic impacts are integrated over time, chemical factors of the sediment and community parameters of the macrobenthos are convenient for environmental monitoring. Threshold values of these factors and parameters that classify fish-farm environments into healthy, cautionary and critical conditions can be roughly estimated from a comparison of Fig. 3 with Fig. 4. These values of sediment and community parameters (Table 1) are useable as environmental quality standards, however further verification in other localities is necessary.

Comparison between ED and ISL

ED and ISL were proposed based on the concept that assimilative capacity of fish-farm environments is determined by waste dispersal and oxygen supply. It was hypothesized that waste dispersal and oxygen supply are influenced by topographic conditions (ED) and by water depth and current velocity (ISL). Surveys of the macrobenthos and environmental factors conducted at the fish farms in Kumano-nada indicate that both indices are indicative of the assimilative capacity of environments. ED is easy to calculate from a nautical chart, and is effective for comparison of the suitability for fish farming between neighboring areas that are located under similar oceanographic conditions. However, to compare fish farms in a variety of topographic situations under different oceanographic and/or geographic conditions this index may be less suitable. ISL incorporates factors of the water depth and current velocity, which are more direct variables that control waste dispersal and loading

(Gowen and Bradbury, 1987; Chamberlain *et al.*, 2001) and oxygen supply (Jørgensen and Revsbech, 1985; Findlay and Watling, 1997). ISL has a wider potential application to assess the suitability of fish farms under a variety of topographical conditions as a simple and effective tool for locating suitable culture sites in coastal areas.

The plaster-ball technique was successfully used to estimate the current velocity at the fish farms in Kumano-nada (Yokoyama *et al.*, 2004). However, a series of checks and calibrations by a current meter may be necessary before use in other localities, because this method needs to be used with caution in different flow environments (Porter *et al.*, 2000). Advantages of using plaster balls are that the device is easy to construct with readily available materials at a low price and that fish farmers can measure the current velocity readily and simultaneously at many stations. The use of plaster balls will be an effective and pragmatic approach to estimate the assimilative capacity of the water body, and to decide the suitable location for fish farming.

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Ecosystem-based management and models in sustainable management of coastal aquaculture

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Abstract To be successful, the complex process of ecosystem-based management requires management tools that can integrate physical, chemical and biological processes, modeling tool must function at multiple scales, be easily understood by non-scientist and above all reliably predict management alternatives. It must address specific questions about bays, lagoons or coastal oceans without the ability to predict the cumulative consequences to large marine ecosystems.

This presentation discusses the concept of ecosystem modeling and focuses on two examples representing small and medium scale semi-enclosed marine ecosystems using a modified coastal ocean circulation model (Blumberg and Mellor 1987). Xincun Lagoon in southeast Hainan Island is a 21.97km^2 (~ 6km X ~ 4km) lagoon with a maximum depth of 10.6m and a 120m-wide outlet to the South China Sea. Xincun City, a major fishing port of ~15,000 people, is on one shore of the lagoon and the other shore is a wildlife reserve. The adjacent lagoon experienced a dramatic growth up to 230ha of fish pen aquaculture in 1996 followed by a catastrophic decline. The natural circulation in the lagoon combined with increased oxygen demand that was created by the fish pens was the likely reason for the disaster. Reducing the number of fish pens (33ha) and the advent of a pearl and macroalgae culture resulted in a more sustainable aquaculture industry and environment. Data indicated that the surface water quality did not violate China's National Water Quality Standards, but the pens were responsible for an estimated 5,000 tonnes of organic pollutants. Fish pens reduced bottom water and sediment quality. Low quality bottom water also flowed in and out of fish pen area with the tide because of the slow turnover time (up to 90 days). Further analysis indicated that macroalgae culture on racks and seagrasses act nutrient scrubbers and could play an important role by reducing ecosystem risk of less desirable algal blooms (Rawson, *et al.* 2002).

The medium scale modeling experiment was conducted on Jiaozhou Bay that is a shallow bay of ~ 400km^2 with an average depth of 7m and maximum of 50m. The adjacent city is Qingdao, which is one of China's largest ports and has a population > 2 million people. During the period of this study the bay cotained three areas of scallop aquaculture pens. Simulation experiments with two-pen stocking densities (12 individual m^{-3} and 24 individuals m^{-3}) indicated that scallops dramatically decreased the concentration of phytoplankton in the culture areas. However, the impact that scallop culture had on nutrient concentrations was small (Chen, *et. al* 1999).

A new management model system has been developed with funding from the Georgia Sea

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Grant Program based on the unstructured grid, finite-volume coastal ocean model (Chen *et al.*, 2003). This system provides a powerful management tool that allows aquaculture to be integrated into the broader context of coastal and large marine ecosystem management. Fed aquaculture does create pollution, but aquaculture is rarely the only pollution source. We must address the issue of aquaculture's contribution to pollution and find practical solutions to these complex problems.

Introduction

For ecosystem-based management to be successful, there must be management tools that integrate the physical, chemical and biological processes. Until recently managers relied on broad science-based regulations and personal knowledge and experience to make judgments about the ecosystem impacts of particular human activities on natural systems. It was the only way to integrate information into an ecosystem approach to management. This, however, leaves managers vulnerable to criticism by political leaders and the broader public community who may not agree with their decisions. Managers need the credibility of a scientific tool that integrates the knowledge of ecosystem processes and the impacts of human activities to guide and to verify their decisions. The output of this scientific tool must be easily grasped by non-scientists and above all it must reliably predict the impacts. The tool also must function at multiple scales. It must address specific questions about bays, lagoons or coastal oceans without losing the ability to predict the cumulative consequences of numerous small and medium scale activities on large marine ecosystems.

New modeling technologies provide powerful management tools that allow us to integrate aquaculture into the broader context of coastal and large marine ecosystem management. Aquaculture cannot be managed outside the context of integrated coastal management. Aquaculture is only one of numerous human activities that add nutrients, organic matter and other pollutants, including some types of aquaculture (fish pens). The aquaculture industry cannot escape the fact that it creates pollution, but it is rarely the only pollution source. The issue of aquaculture's contribution to pollution should be addressed forthrightly and practical solutions developed that integrate carrying capacity into the broader concept of ecosystem management.

Polyculture is one approach to reducing impacts of aquaculture and potentially increasing the carrying capacity of a body of water. Polyculture can utilize both fed and extractive aquaculture to increase the total productivity. Extractive aquaculture, particularly macroalgae and molluscan shellfish, can help reduce nutrients and sequester other pollutants (Yarish, *et al.* 2004).

This presentation will discuss the concept of ecosystem modeling using a modified coastal ocean circulation model (Blumberg and Mellor 1987) and focus on two examples representing small and medium scale semi-enclosed marine ecosystems - Xincun Lagoon, Hainan Province and Jiaozhou Bay, Shandong Province, P. R. China.

Xincun Bay Example

a. Physical Description

Xincun Lagoon in southeast Hainan Island is a 21.97km^2 (~6km X ~4km) gourd-shaped lagoon with a maximum depth of 10.6m and 120m wide outlet to the South China Sea. Xincun City, a major fishing port of ~15,000 people is on one shore of lagoon and the other shore is a wildlife reserve (Figure 1). Aquaculture in the lagoon experienced a dramatic growth in the 1990s, primarily in fish pens. By 1995, fish pens covered 200ha and by 1996 there were up to 230ha of fish pens over much of the central and outlet region of the lagoon. The fish cages used in Xincun Bay are 3m×3m, and are submerged to a depth of 1 to 4m. The shrimp culture industry also thrived and reached a maximum of 100ha ponds in upper reaches of the lagoon. The shrimp ponds were not in the lagoon but their effluent was discharged into it resulting in greater eutrophication. In the 1996,

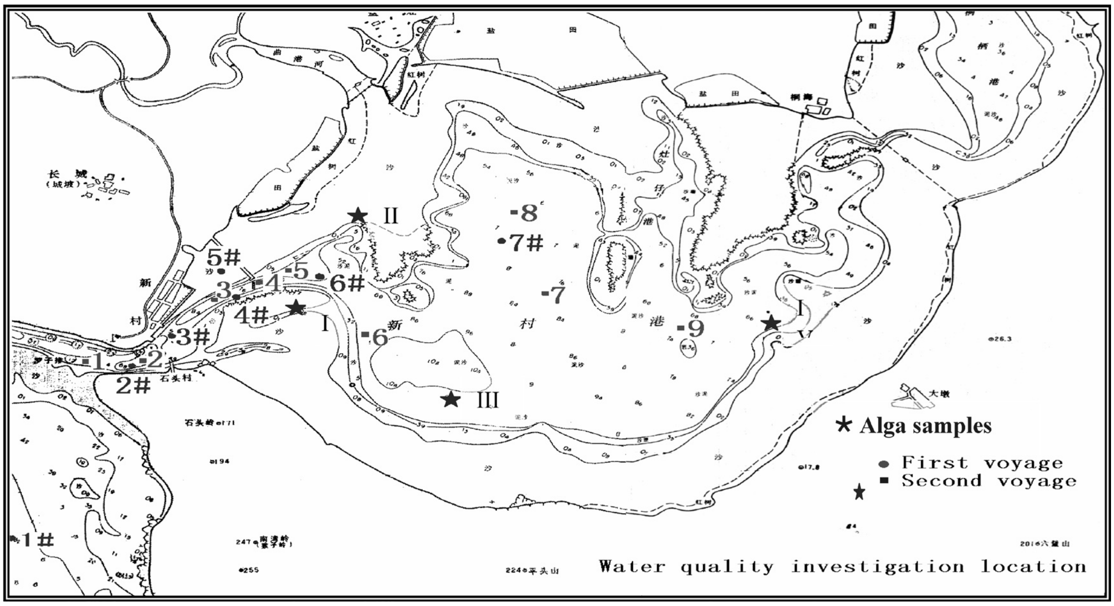

Fig. 1. Map of Xincun Bay with sampling locations

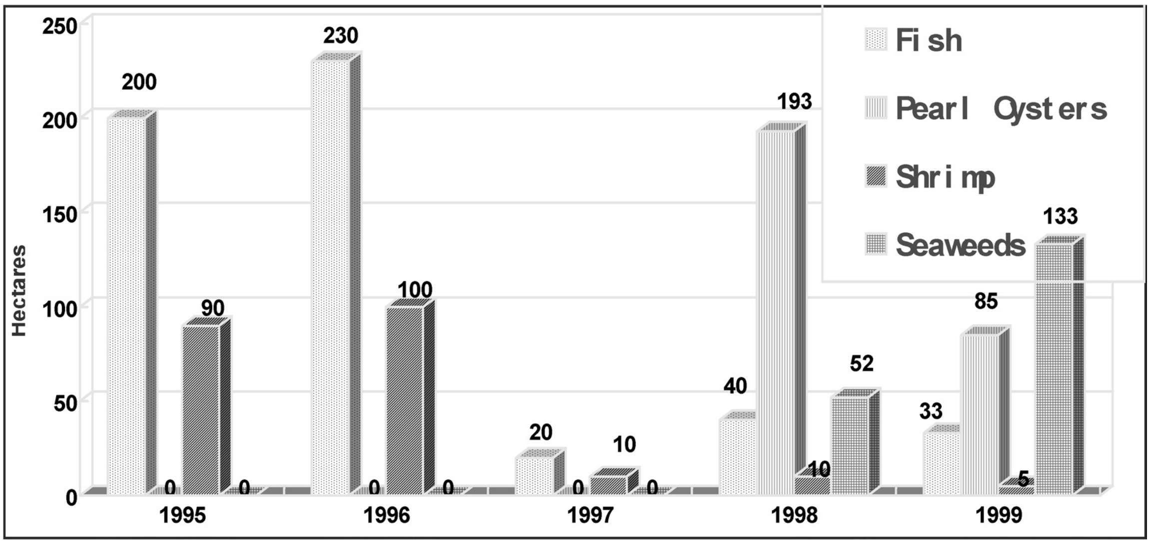

Fig. 2. Histogram of aquaculture area in 90's of Xincun Bay

catastrophic eutrophication of the lagoon occurred and the water quality declined dramatically, The resulting fish kills caused great economic loss and the aquaculture industry collapsed. During 1996, fish pen aquaculture in the lagoon was less than 10% of the coverage at its peak. An area of 20ha near the mouth of the lagoon. In 1998 the industry diversified and added pearl oysters (193ha) and seaweeds (52ha). Knowingly or not, the industry has created a lagoon-wide polyculture system. Pearl oyster culture apparently was not as successful and the coverage was reduced to 85ha. Seaweeds (macroalgae) on the other hand increased by >150% and reach 133ha in 1999 (Figure 2).

As part of the Sino-US Marine Resources Panel cooperative program, two field studies of the lagoon were conducted from July 31 to August 6, 2000. Standard parameters measured included temperature, salinity, COD, DO, DO% saturation, Ph, current speed and direction, turbidity, and tidal level. Primary productivity, nutrients and bacteria communities also were measured. The study results and existing data from earlier sampling was used to create a hydrodynamic model of the lagoon at

The University of Georgia by visiting scientists from the Hainan Marine Development, Planning and Design Research Institute. (Unless otherwise stated references for Xincun Lagoon are excerpted from Rawson *et al.* 2002.)

Analysis of water level data showed that the lagoon has an irregular diurnal tide with a relatively small average range of 69cm with a maximum of 1.55m, which resulted in a slow tidal current velocity. There was a large range in surface velocity, from 2cm s^{-1} to 155cm s^{-1}. The highest surface velocity was at Station 1 in the 120 m-wide-mouth during the spring ebb tide period. During neap tide, the maximum velocity was only 65cm s^{-1}. In the middle of the lagoon, the velocity declined to an average of 10cm s^{-1}. The estimated water flux of 6×10^7 m^3, occurred at spring tide cycle, is one-thirteenth of the lagoon's volume. This might lead one to believe that the lagoon exchanges in ~two weeks, but an earlier study indicated an exchange rate of 90-days. This slow exchange rate means that there is a low capacity to transport pollutants out of the lagoon's ecosystem. The pollutant sources, particular the fish pens, contribute high levels of organic material from the residual ground fish feed, fish respiration and fecal wastes. An estimated 5,000 tonnes per year in organic waste were contributed from the fish pens, compared to an estimated 500 tonnes from Xincun City.

b. Water Quality and Sediment Assessment

Water quality and sediment survey results are shown in Table 1 and Table 2 respectively. Data and times from 14 stations were collected during four cruises on September 10, 1998 and June 28, July 31, and August 7, 2000. The dissolved oxygen concentration was 2% lower than the Class Ⅱ water quality standard, while other water quality parameters were normal (*GB-99*, National water quality standard, P.R. China, 2000). Low dissolved

Table 1. Water Quality Data

Parameter	Max.	Min.	Ave.
Temperature (℃)	30.9	23.6	28.9
Salinity (o/oo)	32.77	28.61	31.78
DO(mg/l^{-1})	6.67	3.92	5.12
DO saturation(%)	97	61.0	87
pH	8.35	8.13	8.26
PO^-_4 ($\mu g\ l^{-1}$)	3.20	1.60	3.72
NO_2 ($\mu g\ l^{-1}$)	1.12	0.14	0.74
NO_3 ($\mu g\ l^{-1}$)	34.3	4.20	10.4
NH_4 ($\mu g l^{-1}$)	165.2	0.56	28.7
Inorganic N ($\mu g l^{-1}$)	176.4	4.9	41.0
Silicate ($\mu g\ l^{-1}$)	865.2	77.8	278.3
COD(mg l^{-1})	1.02	0.28	0.57
Suspended Solids(mg l^{-1})	5.5	0.2	1.84
Bacteria ($\mu g l^{-1}$)	140	0.10	17.4
Chl-a($\mu g\ l^{-1}$)	1.92	0.49	1.24

Table 2. Sediment characteristics at four sampling stations.

St. Num	Sediment Type	Color	Smell	Silicate (mg/kg)	O-Carbon (%)	Organic matter (%)
1	Silt Sand	Black	Rotten	348.04	4.5	7.8
2	Sand	Gray	Non	330.02	0.3	0.5
3	Silt	Gray black	Non	454.53	1.6	2.8
4	Silt	Gray black	Rotten	326.99	0.7	1.2

Note : Cl_{II} The Marine fishery water quality Standard of P. R.China.

oxygen concentration can be the result of the sediment oxygen demand and biological activity in the water column. The sulfate and the organic matter are largely in the sediment. Large organic particles settling in sediment cause a serious water quality problem. Decay processes in the sediment cause a high demand for oxygen from the overlying water column. This demand may excessively stress the oxygen resources of overlying water and deplete the dissolved oxygen concentration. Sediment oxygen demand and the biological decomposition in the water column likely are the major reasons for low dissolved oxygen concentrations in the Xincun Lagoon ecosystem.

Dissolved oxygen concentrations were normal outside the lagoon and in the inner lagoon regions. In the navigational channel region, dissolved oxygen concentrations were low at greater depths. This is the region where fish cage culture is concentrated. The vertical distribution of DO is particularly important in determining the extent to which an area is polluted. The vertical characteristics of DO at different stations located from the outside bay (station 1) to the middle bay (station 7) during the neap tide period as shown in Figure 3. DO is lower than 6mg/L at stations 2 to 6 in all layers. At area stations 2, 4, 5, and 6, the DO is less than 5mg/L, and the average value is only 4.8mg/L. Vertically, DO declines sharply and reaches a minimum 2 to 3 m under the surface in the fish cage culture region. On the other hand, vertical DO distribution is different at station 1 outside the bay; it becomes larger from surface to depth. DO at the surface is 5.04mg/L, very similar to that in stations 2 to 6. At station 1 DO is 6mg/L at depths of 2m. We speculate that this phenomena is the result of the surface water out-flow from the bay. At station 7, where there are no fish cages, water quality is better. DO is 6mg/L at surface, but at depths >3m; the DO value is below 5mg/L (Figure 4).

Nitrate concentrations exhibit a peak of about 5.97 μg/L within the channel region near the cage fish culture, where organic matter falls to the bottom. In both outside lagoon and inner lagoon regions, the nitrate concentration is fairly low with a value of 0.83 to 0.70 μg/L (Figure 4). The nitrate concentration in the inner lagoon is the result of nitrate uptake by the seagrass and it remains generally low.

Ammonium concentrations have a similar distribution to nitrates in the water column. It decreases linearly from the cage fish culture region to an area outside the lagoon. Ammonium concentrations exhibit a peak of about 14.22 μg/L in station 6# in the cage fish culture region, and reduce sharply to 0.09 μg/L in the inner bay where seagrass. beds are dominant (Figure 4).

The phosphorus concentration is commonly lower than nitrate and ammonium concentration in the water column. Phosphorus concentrations are below 0.5 μg/L in six of the seven stations. The maximal phosphorus concentration reaches 1.27 μg/L at station 5# in the fish cage region (Figure 4).

The spatial and temporal distributions of nutrients reflected the dissolved oxygen distribution in the

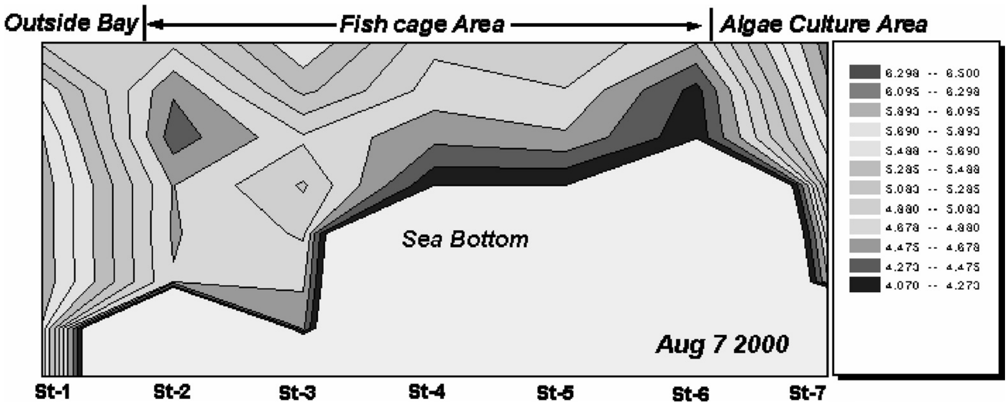

Fig. 3. Dissolved oxygen saturation and salinity in Xincun Bay

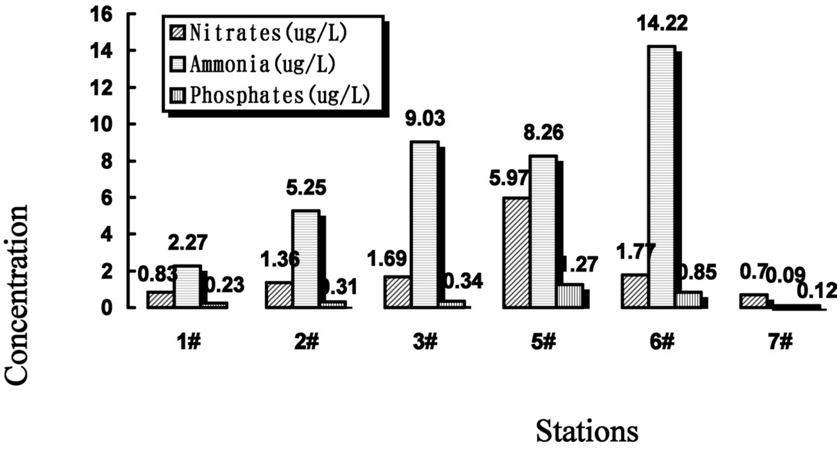

Fig. 4. Nutrient distributions in Xincun Bay.

water column. Within the fish cage area, substantial quantities of organic matter accumulate in the sediment. Sediment oxygen consumption increases as a result of chemical oxidation, activity of benthic organisms, and bacterial decomposition of organic matter. Oxygen in the water column above the sediments can then become depleted, leading to anoxic conditions. When oxygen above the sediments is depleted, nitrogen and phosphorus are released to the water column more readily. Phosphorus is released under anoxic, reducing conditions, whereas it normally complexes with oxidized iron and becomes immobilized. Previous research has examined these relationships between nutrients, dissolved oxygen and sediment oxygen consumption in aquatic systems (Stumm 1973, Frevert. 1980, Nixon 1982).

c. Model Results

A three dimensional conventional water quality analysis simulation model that was originally developed by Ambrose *et al*. in 1993 (known as WASP5) was modified and used to study the dissolved oxygen in Xincun lagoon. The equations solved by WASP5 are based upon the key principle of conservation of mass. They include three major components, the advection and dispersion of transport, kinetic interaction and transformation, and external loading. WASP5 eutrophication water quality model considered eight water quality state variables- DO, PHYT, CBOD, NH_3, NO_3, ON, OPO_4 and OP and used the kinetic framework developed by DiToro *et al.* (1971). In our water quality model, we only consider DO, NH_3, NO_3 and their major kinetic interaction. This is based on evidence that low DO is the major problem of eutrophication, and the nitrate and ammonium concentration are relatively large within the fish cages region in Xincun lagoon.

The two major components of the hypolimnetic oxygen depletion are water column oxygen demand (WOD) and sediment oxygen demand (SOD). WOD embraces the biological and chemical oxygen demand primarily due to algal, bacterial and fish respiration. SOD reflects utilization of dissolved oxygen from overlying and interstitial water of the sediment by biological and chemical oxygen demands. As discussed above, DO which acts as an eutrophication indicator is predominantly low within the fish cage culture region, where much of the organic matter deposits to the sediment. Low chlorophyll *a*, low primarily productivity, even low nutrients in water column, but large quantities of organic matter in sediment, SOD is the major reason for depletion of DO rather than WOD. For this reason, we mainly consider SOD as a important sink of dissolved oxygen in our water quality model. Macroalgal and seagrass photosynthesis and respiration are also considered in this model due to the fact that they remove the nutrients from the water column. Thus, the DO kinetic interaction and transformation includes processes of reaeration, macroalgal (*Kappaphycus alvarezii*) and seagrass (*Enhalus acoroides*) photosynthesis and respiration, cage fish respiration, nitrification and SOD.

Factors that affect SOD are rather complex. These factors include temperature, oxygen concentration, makeup of the biological community, organic and physical characteristics of sediment, current velocity, and chemistry of the interface. Velocity effects on SOD were not due to physical resuspension of bottom material to the overlying water. It was hypothesized that the increase in turbulence generated by increased velocity was responsible for increased transport of soluble organic material across the sediment interface, resulting in high SOD. Measurements of SOD showed that it changes in spatial and temporal variation due to different situations (Hickey 1984, Whittemore 1984).

Within aquatic systems sediment nutrient fluxes play an important role on the nutrient concentration in the water column. Studies indicate that nitrogen and phosphorus may be released to the water column more readily when oxygen above the sediments is depleted (Smith and Fisher 1986). Within the large SOD region, sediments were the dominant sources of ammonium and phosphorus (Boynton and Kemp 1985; Fisher *et al.* 1982). The processes of nutrient fluxes of sediment are complex and it is necessary to calibrate by the in-situ measurement. In our model, we simply consider nutrient fluxes of sediment as the linear relationship with SOD and bottom velocity. The ammonium fluxes and nitrate fluxes ranged between 60 and 600umol/m^2/hour and 3 and 39umol/m^2/hour in the Xincun water quality model.

The water quality model is coupled with the physical model developed by Blumberg and Mellor (1987). The physical model runs prognostic problems with tidal and wind driven oscillations and rainfall water discharge. When the physical model reaches equilibrium state, the water quality parameters are added and run with the cases of (1) a 450 fish cage platforms at the channel region, without the effect of macroalgal culture; (2) double the fish cages, without the effect of macroalgal culture; and (3) double the fish cages and factor in the macroalgal culture.

The model was initialized using the temperature and salinity field on 28 July. The model demonstrates that the temperature and the salinity remain stratified in Xincun lagoon. Tidal cycle average surface temperature and salinity inside the lagoon is uniform with a magnitude of 30.8℃ and 31.8 ppt. Temperature is lower and salinity is high in the deepest part of the lagoon. Outside of the entrance of the lagoon, a strong gradient of temperature and salinity is demonstrated by the effect of flood and ebb tidal current.

A uniform DO, NH_4, NO_3 field is initialized after the temperature and salinity field is adjusted. Figure 5 shows the spatial and temporal distribution of DO concentration in cases (1) and (2). The distribution of DO is closely related to the tide, during flood tide (upper Figure 5), the minimum DO concentration center occurs not in the channel cage fish culture region but in the inner Bay. During ebb tide, the minimum DO occurs in the outside lagoon near the entrance. The lowest DO concentration occurs in the cage fish culture region only during the middle flood-ebb tide. In cases (1) and (2), the lowest DO concentration is 5.0mg/L and 4.5mg/L, respectively. The experiments demonstrate that the tidal average DO concentration reduces 10% when the fish cages are doubled. It seems that the effect of cage fish in the model is not sensitive to the DO concentration. The response of this process indicates that strong tidal currents in the channel region enhance mixing with outside bay water and increases DO concentration.

The DO concentration distribution in selected area 1 had a stratified structure with the lowest DO over the sediments in the channel region. Large SOD in the fish cage region consumes dissolved oxygen and leads to the DO concentration depletion.

When macroalgal culture is considered in sites Area 2 and site Area 3 that are further in the lagoon, macroalgae seem to not enhance the DO concentration in fish cage region and, obviously, in the macroalgal culture regions. The change of DO concentration in selected points of the bay, fish cage region and inner bay. Co-incides with the tidal elevation (tidal current). In the fish cage region, lowest DO concentration occurs before lowest tidal with a magnitude of 4.2mg/L at the bottom; highest DO concentration occurs at the beginning of flood with a magnitude of 5.5mg/L. But in the open part of the lagoon where macroalgae are cultured, the

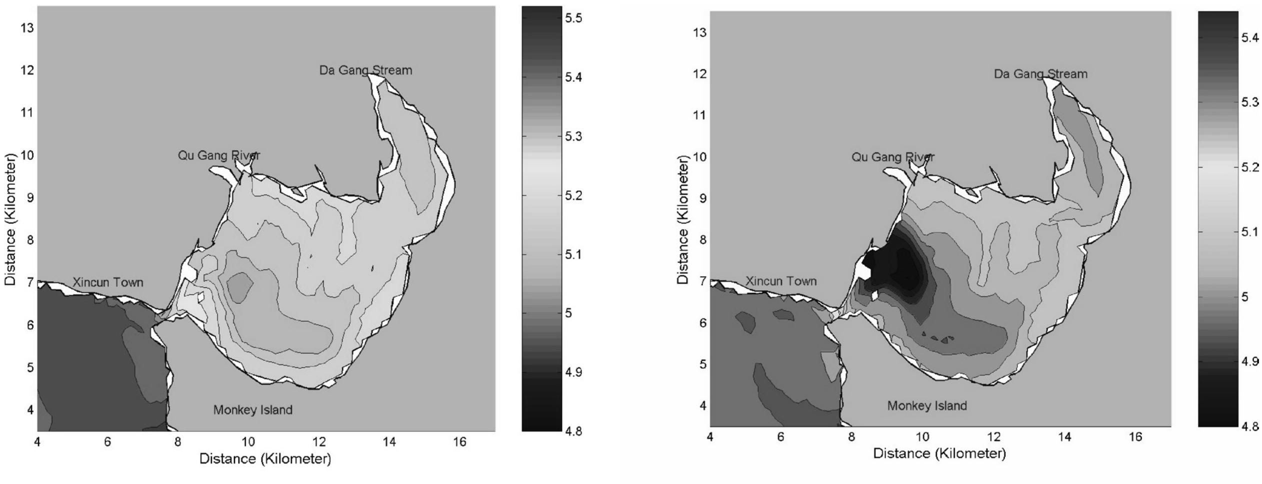

Figure 5

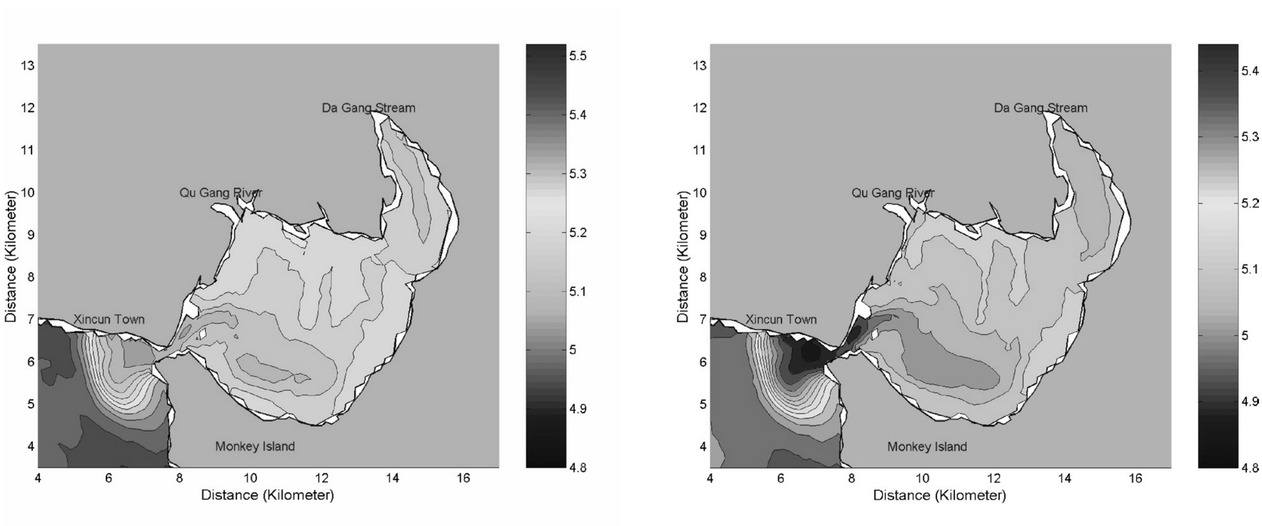

Figure 5.

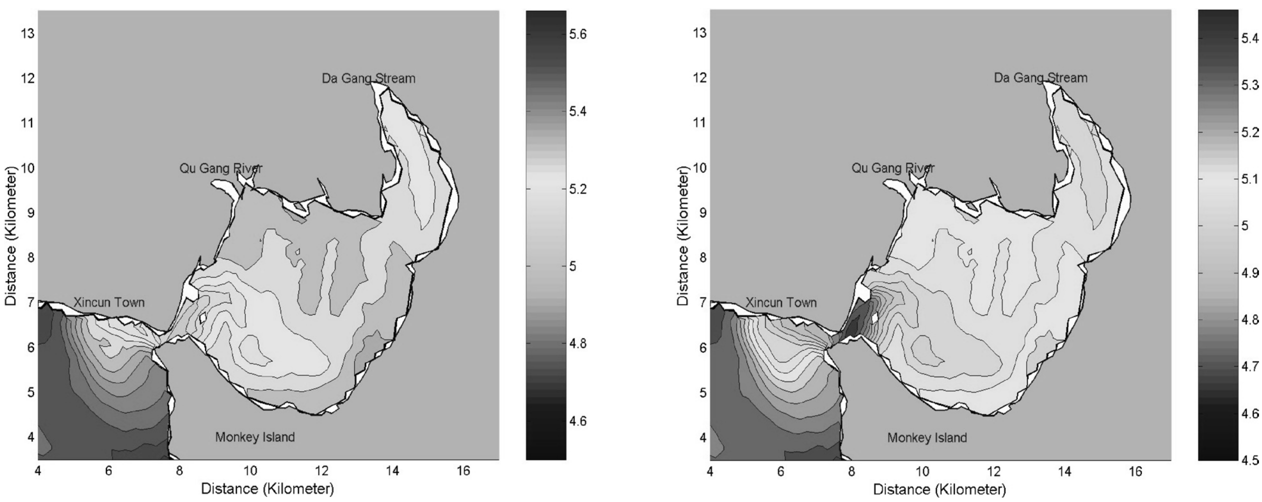

Fig. 5. DO concentration distribution during the flood tide (upper pair), ebb tide (middle pair), flood-ebb tide (lower pair) under existing conditions (left) and with a 50% increase of fish cages (right) in Xincun Bay.

surface DO concentration seems unchanged, and the bottom DO concentration reaches a lowest value of 4.8mg/L.

d. Follow up sampling on Xincun Lagoon

Since the 2000 study, the aquaculture mix in and around the lagoon has changed. The number of 3m X 3m fish cages increased substantially in 2001 to 6,500 cages (87ha) then decreased to steadily to 5,200 (70ha) (Table 3). (Fish pen platforms usually have nine cages).). The macroalgae *Kappaphycus alvareezii* culture increased during the 2001 to 2004 period from 146ha to 233ha and the shrimp ponds adjacent to the lagoon are 200ha. The Hainan Marine Development, Planning and Design Research Institute continues to monitor the lagoon. The most obvious change is the continued increase in the average ammonia levels in the lagoon from 28.7 μ

Table 3. Area of culture species (hectare)

Year	Fish cane Culture (Ind./hectare)	Eucheuma Macroagale	Shrimp pool
2001	6500/87	146	200
2002	6400/85	200	200
2003	6200/80	213	200
2004	5200/70	233	200

Personal communication: Wang DaoRu, Hainan Marine Development Planning Design Research Institute, Hainan, P.R. China

Table 4. Water quality monitoring results in 2003

Content	Min.	Max.	Ave.	Water quality standards (P.RChina) Class I	Class II
Salinity	32.645	33.655	33.286		
Ph	8.24	8.29	8.27	7.8-8.5	
Do	5.31	6.73	6.09	>6	>5
COD	0.27	0.73	0.47	<=2	<=3
NO3(μg/l)	12.041	17.501	14.561		
NO2(μg/l)	0.420	1.680	1.092		
NH(μg/l)	11.481	47.746	29.262		
IN(μg/l)	0.026	0.066	0.045	<=0.20	
<=0.30					
IP(μg/l)	0.002	0.014	0.008	<=0.015	
<=0.03					
Chl--a (μg/ l)	0.02	0.1	0.05		

Table 5. Water quality monitoring results in 2004

Content	Min	Max	Ave.	Water quality standards (P.R China) Class I	Class II
Salinity	32.645	33.655	33.286		
Ph	8.15	8.29	8.27	7.8-8.5	
Do	5.68	6.46	6.1	>6	>5
COD	0.62	0.99	0.81	<=2	<=3
NO3(μg/l)	12.041	17.501	14.561		
NO2(μg/l)	0.420	1.680	1.092		
NH(μg/l)	26.481	67.746	49.262		
Chl--a (μg/ l)	0.35	0.71	0.5		

Rawson, Mac C. Chen, R. Ji, M.Zhu, D. Wang, L. Wang, C. Yarish, J. Sullivan, T. Chopin and R. Carmon, 2002 Understanding the Interaction of Extractive and Fed Aquaculture Using Ecosystem Modelling, in: Responsible Marine Aquaculture, R. Stickney and J.P. Mcvey, eds. CABI publishing, Oxford UK.

g/l in 2000 to 49.3 μg/l in 2004 (Tables 4 & 5) The model simulations pointed out that the water column in the fish cage area was heavily polluted by organic matter. The resulting low DO was an indication that carrying capacity has been exceeded and the impact of the fish culture must be reduced. Since the study took place four years ago, the fish cages and shrimp ponds numbers have been limited and the number of cages reduced. Also, the ecological importance of the seagrass has been recognized and a new seasgrass special protected zone set up (Wang DaoRu, personal communications).

e. Discussion of Xincun Lagoon Results

The results showed that the water column in the Xincun Lagoon aquaculture region was heavily polluted by organic material and according to sediment sample analysis, was also high in silicate contents. Except for dissolved oxygen, sampled chemical parameters and nutrients did not exceed the national water quality standards Class Ⅰ. The data were also evaluated according to Criteria for Surface Water Quality Classifications, Class Ⅱ (Florida EPA). Although the water generally met standards, the environmental health of the fish cage culture and navigation channel region has declined considerably as evidenced by the mortality of cultured fish and low DO.

Two kinds of pollutants affect water quality and sediment quality in Xincun Lagoon. One source is the pollutant produced by four factories, four restaurants and seven gasoline stations, and an estimated 481tons of COD from the sewage discharging. The other pollutant is a by-product of fish cage operations that results in an estimated 5,000tons of organic pollutants annually. Water quality samples indicate that DO is always lower than the value of national water quality standards in fish culture areas. The assessment results show the main source of pollution is the fish cages. When feeding fish, large amounts of uneaten food and feces descend to the bottom. Sediment under the pens releases NH_3H_2S and other pollutants by degradation of the organic matter by bacteria. This chemical reaction requires large quantities of oxygen and reduces the dissolved oxygen substantially in the sediment and water column. Results of DO concentration-modeling support the above viewpoint. The model experiments also show that average DO concentration will decrease by about 10% when fish cages are doubled. This result shows the effect of strong tidal current mixing and transport. Macroalgal culture increases the DO concentration in the culture region, but contributes less to the DO concentration in the cage fish region

Ⅳ. Jiaozhou Bay Example

a. Physical Description

Jiaozhou Bay is a shallow bay of ~ 400 km^2 with an average depth of m and maximum of 50m. The adjacent city is Qingdao, which is one of top five ports in China and has a population >2 million people. During the period of this study the bay contain three areas of scallop aquaculture pens (Chen, *et al.* 1999).

b. The Model

The physical model used in this study was a modified version of the coastal ocean circulation model developed by Blumberg and Mellor (1987). The model's forcing functions are: (1) tidal oscillations, (2) wind driven features, and (3) time-variable inputs of rivers. The time-variable river inputs and onshore intake/outflow discharges were used to simulate the buoyancy flow caused by river discharges. By far, the largest river discharge (85%) into Jiaozhou Bay during summer was from the Dagu River ($87m^3\ s^{-1}$, Liu and Wang, 1992). The effects of wind-induced currents and resulting mixing influences on the distribution of temperature, salinity, nutrients, and phytoplankton were examined in the simulations. The dominant wind forcing in the summer is from strong southeast winds, but for simplification, a constant southeasterly wind of 5m s^{-1} was added into the model after 10 model days.

The coupled biological model simulates simple nutrients (N), phytoplankton (P), and zooplankton (Z) using a modified model developed by Franks and Chen (1986). The biological parameters varied widely in time and space. The model was run with an initial set of parameters. Sensitivity analyses were then run over the parameter range. The stock density of shellfish was calculated directly from measurements taken in Jiaozhou Bay in 1996 (Collaudin, 1996). The scallop rafts consist of vertical lines of lantern nets. Based on the average number per lantern net, the standing stock parameter was set at 12 individuals m^{-3} that is the equivalent to 0.012 individuals L^{-1}. The scallop filtration rate varies in a range of 30 to 200L d^{-} $individual^{-1}$ at around 25℃. This may overestimate the filtration rates since the food availability was not taken into account (Winter, 1978). So, a filtration rate of 100L d^{-1} $individual^{-1}$ was used in the model. The excretion fraction of the filtered food was assumed to be 0.3 or 30%.

Jiaozhou Bay is a phosphorus-limited ecosystem, and in the experiments, phytoplankton and zooplankton were measured in units of carbon (C) and nutrients by units of phosphorus (P). A constant C/P ratio of 100 was used to convert carbon to phosphorus. A 60C/Chl *a* ratio was used to convert chlorophyll *a* to carbon.

c. Effects of Aquaculture

Simulation experiments were made with two scallop stocking densities of 12 individuals m^{-3} (0.012 individuals L^{-1}) in the first case and 24 individuals m^{-3} in the second case. In both cases, scallops were grazing dramatically and decreased concentrations of phytoplankton in the culture areas labeled A1 to

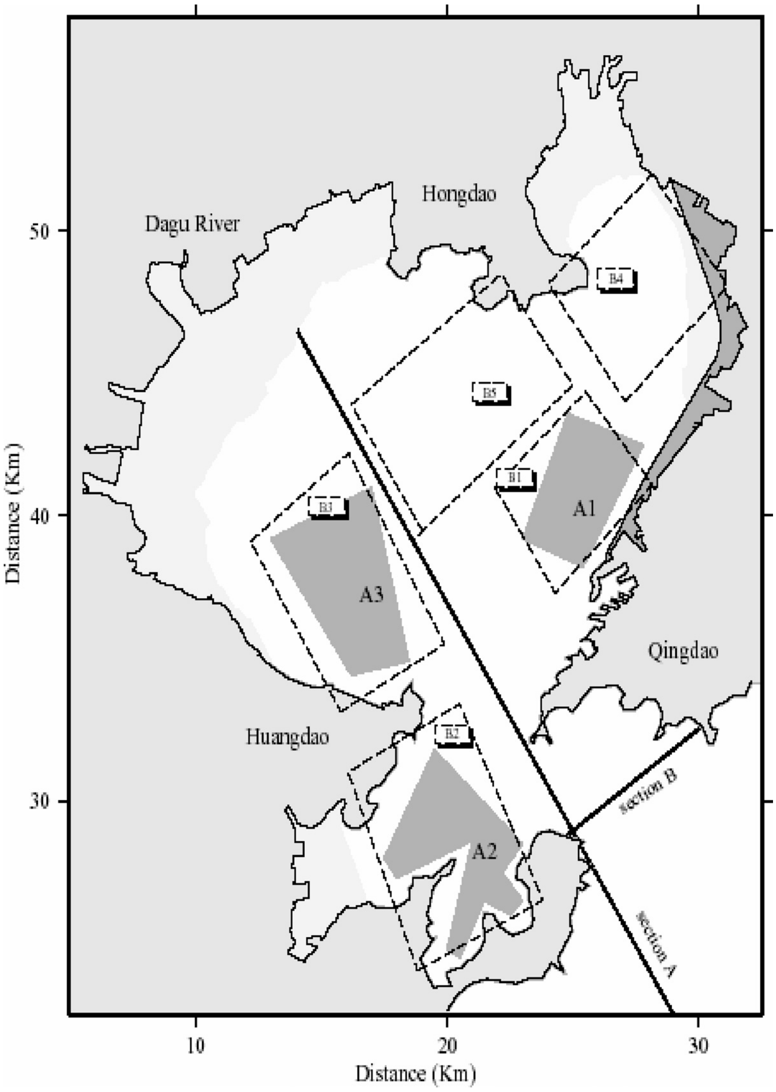

Fig. 6. Locations of the shellfish aquaculture sites (shaded area) and selected regions for the flux estimation of nutrient and phytoplankton (areas enclosed by dashed line). (The heavy solid lines indicate two sections used to represent our model results on cross-bay section (section A) and flux calculation into of out of the Bay (section B).

A3 (Figure 6, Chen *et al.*, 1999). The experiments suggested that the scallops would sharply reduce the concentration of phytoplankton to 0.99 μg Chl *a* L^{-1} in A1, 0.52 μg Chl *a* L^{-1} in A2, and 1.0 μg Chl *a* L^{-1} in A3, about 31.8%, 33.3% and 37.3% lower than those in the case without shellfish (Plate 2, Chen *et al.*, 1999). The response of phytoplankton to increased shellfish stocking densities was not linear. When the stocking density was doubled to 24 individuals m^{-3} the concentrations decreased to 0.71 μg Chl *a* L^{-1} in A1, 0.38 μg Chl *a* L^{-1} in A2, and 0.67 μg Chl *a* L^{-1} in A3. These concentrations were ~ 51.1%, 50.8% and 55.6% lower than the case without shellfish, but only 19%, 18% and 22% lower than the first case with shellfish (Figure 7, Chen *et al.*, 1999).

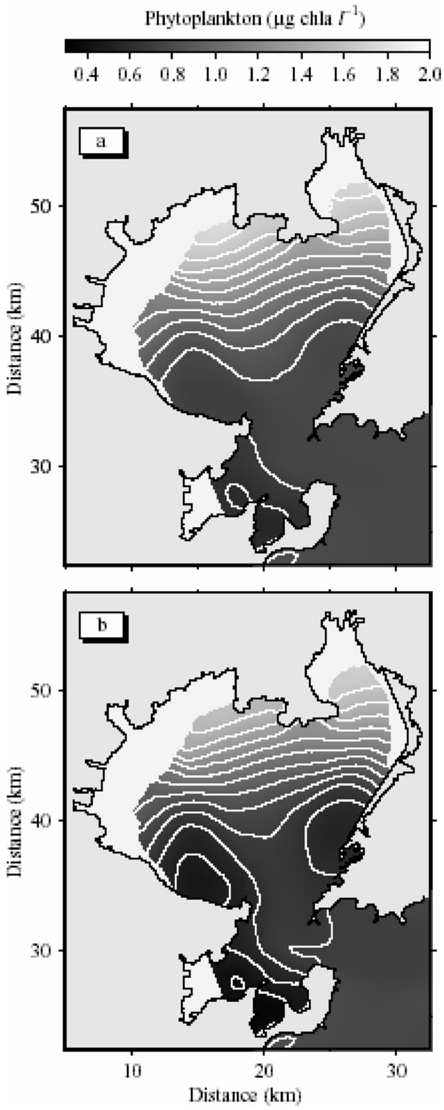

Fig. 7. Tidal-cycle averaged surface distribution of phytoplankton at the 20 model days for the case with the shellfish culture densities of (a) 12 and (b) 24 individuals m^{-3}. Physical forcings are tide, freshwater discharge and a southeasterly wind (5 ms^{-1}).

The impact of scallop culture on the concentration of nutrients was very small, even at the higher stocking density. This is in contrast to previous studies which indicated that shellfish have an important role in nutrient cycling and distribution (Dame, 1993). One explanation is that Chen's model did not consider the impact of the biodeposition process of shellfish. The biodeposition process could result in shellfish taking up small particulate organic matter and producing feces and pseudo-feces that decompose into inorganic nutrients. Our model did include shellfish excretion, which was directly converted to phosphates. If the above explanation is correct, there should be significant modification of nutrient concentrations when the excretion rate or stocking density is increased. However, that was not the case in simulation experiments. Another possible explanation is that most of the phosphates in Jiaozhou Bay were the result of loading from the land and rivers. The recycling of nutrients by shellfish may directly influence the concentration of nitrogen but not phosphates, or the nutrient regeneration rate may be orders of magnitude smaller than the nutrient loading rate from other sources.

d. Nutrient Uptake and Regeneration

To understand the roles of biological processes, the nutrient uptake and regeneration processes in the coupled model must be examined. Nutrient uptake in this modified NPZ model was controlled by the phytoplankton growth rate, incident radiance, the half-saturation constant, phytoplankton biomass and nutrient concentration. Nutrient regeneration was estimated by the sum of zooplankton excretion, death of phytoplankton and zooplankton, and shellfish excretion.

In the case with only tides and freshwater discharges, the model indicated that surface distributions of the uptake and regeneration rates were similar to nutrient distribution, which decreased from the inner to outer bay with the highest values on the northwestern and northern coasts. The maximum regeneration rate in the inner bay was $\sim 2\,\mu$mol C L^{-1} d^{-1}, which was ~ 5 times smaller than the maximum uptake rate. This suggests that the physical process associated with river discharge was a major source of nutrients for phytoplankton in the inner bay. Adding a southerly wind did not significantly change the distributions of nutrient uptake or regeneration. The uptake rate was relatively large in the inner bay along the coast as a result of nutrient accumulation by the wind-induced northwestward advection. This phenomenon may explain why a phytoplankton bloom occurs in the innermost bay during a southeasterly wind.

When consumption of phytoplankton by shellfish was included, distribution of nutrient uptake and regeneration was modified, particularly in the aquaculture areas. Nutrient uptake rates in the aquaculture sites dramatically decreased because the phytoplankton decreased. Yet, the nutrient regeneration rate in these sites increased as a result of shellfish metabolism. As a result, the distribution of phosphates was similar in the case with and without shellfish aquaculture, suggesting that the decrease in nutrient uptake rates due to phytoplankton consumption was almost compensated for by the physical processes of advection and diffusion.

One of the main interests in this study was to identify, qualify and quantify the roles of physical and biological processes in maintaining ecosystem health. In the simple NPZ food web, the physical processes included advection and diffusion, M_2 tide, river discharge and wind. Biological processes related to phytoplankton included nutrient uptake and regeneration, phytoplankton grazing and mortality, and shellfish consumption. To examine effects of freshwater discharge and shellfish aquaculture, the net flux of nutrients and phytoplankton in five closed regions and across the outer strait were estimated. The flux was calculated based on tidally averaged values over the 10 tidal cycles. When we say “equilibrium state,” that means the flux is balanced for a first-order approximation in which the biological field changes slowly but no steady state could be reached over the course of the study period. Sensitivity analysis of the phytoplankton revealed that the spatial distribution of phytoplankton remained unchanged, although the concentration varied remarkably with changes in parameters. This suggests that the model results for phytoplankton were robust.

The model results revealed that physical processes had a direct impact on temporal and spatial distributions of nutrients and phytoplankton as well as on shellfish aquaculture. Tidal mixing caused physical and biological variables to be well mixed vertically. The concentrations of nutrients and phytoplankton were high near the northwestern and northern coasts near river sources but decreased from the inner bay to the outer bay. The model results suggested that prevailing river discharges and tidal mixing, and the southeasterly wind in the summer may cause unusual nutrient accumulation and lead to phytoplankton blooms in the innermost bay. The fact that a phytoplankton bloom can occur under a condition of southeasterly wind implies that physical processes may have a direct impact on the occurrence of “red tide” along the northern coast of Jiaozhou Bay. The overloading of nutrients from inland shrimp aquaculture, industries and other urban human activities caused a high nutrient concentration in the inner bay that provided favorable conditions for eutrophication. Accumulation of nutrients due to the southeasterly wind speeds up the eutrophication process and causes the “red tide”.

The estimation of nutrient and phytoplankton fluxes in the five identified sites suggested that the nutrients were maintained by physical processes, while the phytoplankton was controlled predominantly by biological processes. Shellfish aquaculture tended to alter the entire Jiaozhou Bay ecosystem. The loss of phytoplankton in shellfish aquaculture sites was compensated by nutrients that advected and diffused from surrounding waters. High levels of phytoplankton consumption also caused a net flux of phytoplankton into the bay from the Yellow Sea, even though nutrients were advected out of the bay. In addition to eutrophication caused by human activities, high densities of suspended feeding shellfish will alter the lower trophic food web by grazing phytoplankton, excretion and biodeposition. Aquaculture populations of bivalves tended to transfer large quantities of materials from the water column to the sediment, which can dramatically change the content of the organic matter in the benthic layer (Kautsky and Evans, 1987; Kasper *et al.*, 1985). The benthic processes, in turn, may alter nutrient cycling in the bay (Barg, 1992; Dame, 1993; Jorgensen, 1990). It also should be noted that this model did not include the intertidal zone. The direct impact of the intertidal process remains unclear, but a large quantity of nutrients potentially can be advected back to the bay during ebb tide.

Ⅲ. Conclusion

Management of aquaculture in semi-enclosed embayments is influenced by numerous physical, chemical and biological processes. Resource managers who are tasked with maintaining and improving environmental quality must balance the multiple uses of bays. Three-dimensional models provide tools that can help determine carrying capacity for aquaculture by integrating knowledge of physical, chemical and biological processes and accounting for multiple sources of pollutants. The models also will provide credibility to the decisions of managers and allow the development of sustainable aquaculture in locations throughout the world.

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Offshore finfish mariculture in the Strait of Juan de Fuca

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Abstract Finfish mariculture has existed in the U.S. Pacific Northwest for over thirty years, but for the past 15 years most effort has focused on culture of Atlantic salmon in protected, inshore cage sites. The Strait of Juan de Fuca (the "Strait") is a large area with relatively sparse shoreline development and several apparent advantages for mariculture using offshore technology.

This study provides an overview of pertinent hydrographic conditions and possible water quality effects of marine or salmonid finfish culture in the Strait for commercial harvest or stock rehabilitation. Circulation studies, current and wave meter deployments, acoustic Doppler current profiles and phytoplankton assessments were conducted in three different regions distributed throughout the Strait near the southern, U.S. shore. Results were compared to existing inshore fish farms and analyzed with a simulation model (AquaModel) that accounts for growth and metabolic oxygen demands of caged fish and the response of phytoplankton to nutrients and grazing. An available benthic submodel was not used as current velocities throughout the water column and near the sea bottom far exceed known threshold rates for salmon farm waste resuspension. Such strong currents allow for dispersal of the organic wastes and their aerobic assimilation into the food web.

The field study results and modeling indicate no probable adverse effect of large scale fish mariculture in the Strait with regard to sedimentation or water column effects. Phytoplankton growth stimulation as a result of fish culture will not occur because nutrients do not limit microalgal growth. The area is naturally replete with dissolved inorganic nitrogen and sunlight is the primary factor limiting phytoplankton growth. Similarly, background nitrogen levels exceed half-saturation rates of seaweeds and farm plume dispersal is mostly parallel to shore in deep water so no effect on seaweeds is anticipated. Fish-killing harmful algae were rarely observed and then only in sparse numbers, although harmful Heterosigma akashiwo are known to occur throughout the waters of the Strait, Puget Sound and adjacent waters of the Pacific Ocean. Growing season phytoplankton abundance is much lower in the Strait than in nearby bays or Puget Sound.

Previously undetected and persistently lower sea surface temperatures were observed in satellite imagery for the central Strait region, especially during the summer and early fall. Surface-layer water temperature was positively correlated with dissolved oxygen concentration during the same seasons. Accordingly, there could be significantly reduced dissolved oxygen content of surface waters of the central Strait during this period, but this finding requires field verification. Eastern and western areas of the Strait may be marginally better for fish culture on this account, depending on fish species cultured.

We conclude that effects of marine fish mariculture on water quality or benthic conditions would be insignificant and that fish culture is technically feasible in the Strait. However, the high energy environment and challenging conditions will necessitate revised and novel management techniques to insure successful operations.

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Introduction

Though more than half the world's salmon and shrimp sold annually are now produced by aquaculture, very little of the marine white fish is farmed. As technical obstacles are overcome, many now believe that farming or stock enhancement of marine fish is a developing opportunity. It may be more than just a business opportunity; it potentially is the solution to a chronic problem of over-harvesting and resource depletion in many of the world's wild capture fisheries. But done improperly, mariculture could damage marine ecosystems and to deprive us of the seafood on which humans have come to depend. Modern, environmentally-sensitive aquaculture using low or no adverse environmental impact methods has been achieved at nearshore fish mariculture sites in Washington State (NOAA 2001, Rensel 2001) after environmental guidelines were adopted 20 years ago (SAIC 1986). A goal for the future of all mariculture is one in which our seafood harvests and the environment that supports them are in natural balance.

In recent years there has been increasing private and government interest in aquaculture "offshore" or in the "open ocean" in the nation's coastal waters. In some cases in the U.S. this could mean operating beyond the three mile State jurisdiction, in the Exclusive Economic Zone (EEZ) but in many cases, due to siting limitations of water depth, it would be nearer shore but in exposed locations. Advocates suggest that the only remaining opportunity for mariculture siting is offshore, due to space limitations and conflicting uses nearshore. Opponents raise several issues including nutrient enrichment and possible adverse benthic effects.

Already a few such offshore projects are operating in the U.S. as research or commercial businesses, mostly in Hawaii and Puerto Rico but more are being located overseas. Although not truly "offshore" in terms of distance from the coast, or being outside state or province jurisdiction, the Strait of Juan de Fuca (The "Strait") between Washington State and British Columbia is being considered for marine fish mariculture. The exposed, high energy nature of its waters means that offshore equipment and methods will have to be used if it is to be done successfully. Potential exists especially for the commercial culture and/or restoration of stocks of marine fish such as rockfish (*Sebastes* spp.), lingcod (*Ophiodon elongates*) or sablefish ("*blackcod*" *Anoplopoma fimbria*), culture techniques for which have now been developed (Ikehara and Nagahara 1980, Whyte *et al.* 1994, Clark *et al.* 1999, Rust *et al.* 2006).

The results of our study are reported in detail in a literature review and annual reports prepared for the U.S. NOAA Sea Grant Office that are all available via internet link in references (Rensel and Forster 2002, 2003, 2004). The literature review indicated that few multi-year hydrographic studies had been published for the western and central Strait and most were single year studies with monthly data collection. Studies conducted many decades ago, although done to high standards at the time, did not account for interannual and shorter temporal variation, which is known to be significant, as discussed below. Routine hydrographic monitoring of the eastern Strait began in 1999 and has shown some of this variability, such as occurred during a severe drought in 2000 and 2001 (Newton *et al.* 2003). Our sampling of the Strait began in the late summer of 2001, but as explained below, the system had apparently not returned to normal conditions by then. At that time we documented unusually low dissolved oxygen concentrations for surface and near surface waters in several locations. As a result, the subsequent years' work included a focus on dissolved oxygen conditions or surrogate measures, as discussed below.

Our study considered the siting of fish mariculture projects in the Strait in relation to key physical (water depth, tidal velocity and near-field circulation), biological (phytoplankton) and chemical factors (dissolved oxygen, water temperature and dissolved nutrient) conditions. Other biological issues such as effects of escapes, use of limited fish meal and oil or possible disease consequences are not discussed here. Socio-political aspects of mariculture siting such as competition with existing fisheries, avoidance of navigation lanes and concentrated fishing areas, maintenance of visual and auditory aesthetics for nearby shoreline owners, etc. are important too. However, they are not discussed in

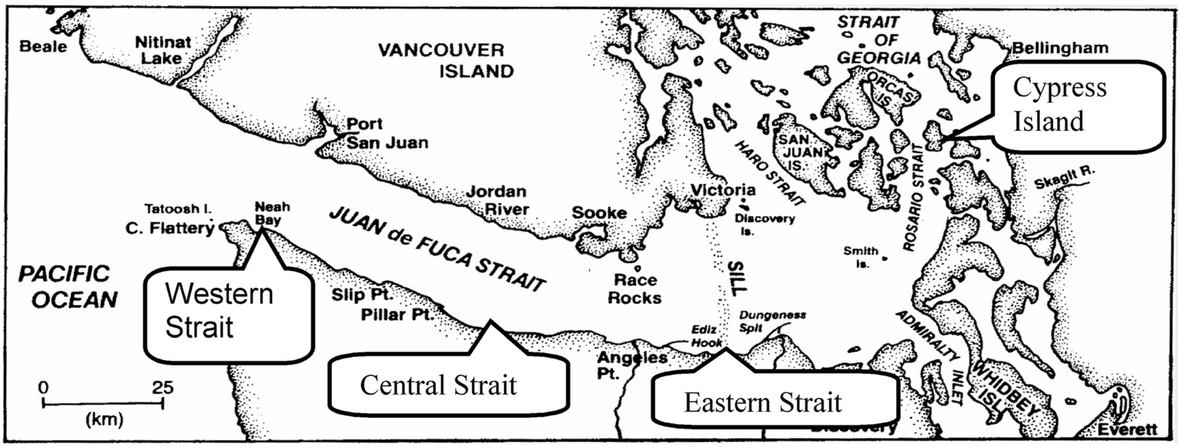

Fig. 1. Study area locations in western Strait (offshore of Neah Bay), central Strait (offshore of Whiskey Creek), Eastern Strait (offshore of Green Point to Morse Creek) and reference station at Cypress Island in North Puget Sound. Base figure from Thomson 1981, used with permission.

this paper except to the extent that our study areas were selected with prior knowledge that such areas were likely to be suitable with regards to these other considerations.

Fish mariculture is technically possible in many locations in the Strait but we selected three study areas, one each in the western, central and eastern Strait. These are referred to as 1) Offshore of Neah Bay, 2) Offshore of Whiskey Creek and 3) Offshore of Green Point (actually between Morse Creek and Green Point), respectively (Fig. 1). Also included for comparison was a reference area at Deepwater Bay, Cypress Island in north Puget Sound where fish mariculture has been practiced and environmentally monitored for several decades.

Additional details and literature reviews are reported in the underlying technical papers available from the primary author or from NOAA or at http://www.wfga.net/sjdf/index.html. Here we only include a partial overview of some of the results from our study in the 20 to 40 m depth zone of the subject area.

Current Velocities and Circulation

Current velocity is a primary consideration for fish culture in net pens both in regard to its effect on cultured fish and to potential impacts on the benthos and water column. Presently, sites considered optimal for fish mariculture in pens have current velocity in the range of 10 to 60 cm s^{-1} but varies within this range depending on size and species of fish, stocking density and pen design or configuration. Regular resuspension and dispersal of salmon farm wastes occurs at near-seabed current velocities in the range of ~10 to 26 cm s^{-1} Cromey *et al.* 2002). Such dispersal allows the aerobic decomposition of wastes and avoids the extirpation of benthic infauna beneath of near net pens under optimum conditions.

At higher current velocity, fish may have to be sized appropriately and cage systems reinforced. At mean velocities lower than 5 to 10 cm s^{-1} (depending on the fish species and feed size) significant adverse sedimentation effects on the benthos are possible beneath or adjacent to the cages, although some sites in other areas may be episodically flushed by storm events. The minimal recommended average current velocity for near surface and midwater depths combined in Washington State is 5 cm s^{-1} (SAIC 1986). Other physical factors besides current velocity factors have a bearing on site suitability too, such as depth beneath pens, but in the Pacific Northwest and in Maine it is believed that current velocity is relatively more important than depth beneath cages to minimize benthic impacts (Cross 1993). Current and wave meters were deployed at all sites and acoustic Doppler current profilers with bottom tracking were used on vessels to survey during varying types of tidal amplitude cycles.

Drogue tracking was also used; see Rensel and Forster (2003, 2004).

Current velocity distributions for surface cage mean depth of 5 m in the western and central Strait locations were skewed with maximum velocity near 100 cm sec^{-1} (Fig. 2). Mean current velocity was ~32 cm sec^{-1} at both locations. At the location offshore Neah Bay, direction of flow was parallel to shore and equally distributed in both seaward (westerly) and easterly directions (50% each of total the 2,590 observations, directions within 180 degree arc of perpendicular bearing from shore) suggesting no net outflow during the winter time period. Net outflow at the nearshore locations sampled would be expected to increase in spring and early summer coincident with increasing river flow from the Georgia Strait-Puget Sound Basins. Periodic winter main channel and summer nearshore current reversals that last for several days are also not uncommon (Cannon 1978, Thomson et al. 2004).

A major difference between the Strait and inshore waters of Puget Sound is the temporal extent of slack tide between tidal phases periods, herein defined as periods of current velocity < 2 cm sec^{-1}. Offshore of Neah Bay slack tidal periods averaged only about one minute per day versus an estimated hour or more at a typical Puget Sound net pen site. In commercial fish mariculture, extended slack tide periods may result in depressed dissolved oxygen concentrations within the pens, sometimes causing damaging physiological stress on cultured fish. Offshore spar cages performed well in early trials offshore of Whiskey Creek in 1991 to 1993, as did the Atlantic salmon cultured within them (Loverich and Croker 1997). The strength and persistence of currents in the study areas are more than sufficient to prevent adverse benthic sedimentation effects, i.e., reduced benthic diversity and species composition changes. But such strong currents present challenges for mariculture operation and maintenance. Pacific Northwest fish farmers typically move cages, adjust anchoring systems and perform diving inspections outside of pens during slow currents or slack tides, conditions that are relatively infrequent in the Strait. The observed currents at our study sites, adjusted for deflection of currents (Inoue 1972), are also suitable for culture of appropriately-sized salmonids, but it is unknown how various sizes and species of marine fish species would respond to them. Effect of strong current velocity on marine fish culture is a topic requiring further research and experimentation.

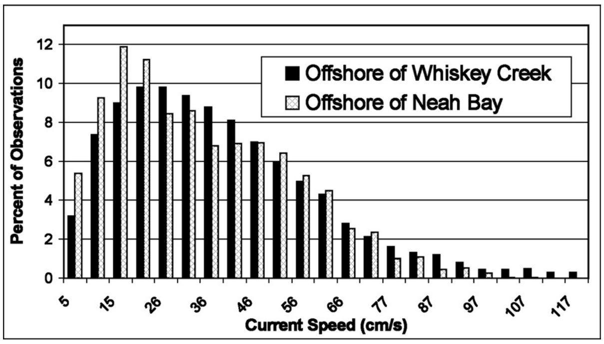

Fig. 2. Velocity distribution for 5 m depth (MLLW) current meter data offshore of Whiskey Creek and offshore of Neah Bay.

Wave Exposure

Wind waves and oceanic swell are major considerations for any form of mariculture. Oceanic swell is periodically encountered in the Strait, especially the west end, but large wind waves may be encountered anywhere in the Strait, depending on season and weather. Wind waves are particularly common in the afternoons from late spring through early autumn when westerly or sometimes easterly sea breezes funnel through the Strait (Renner 1993, Thomson 1994). Wave amplitude and frequency data offshore of Neah Bay were collected from December 2001 through January 2002 (Fig. 3). Significant wave height ranged from 0.2 to 2.2 m and was dominated by long period (~15 s) waves. These conditions do not exceed design criteria for several types of offshore cages. Moreover, wave frequency was not positively correlated with wave height (r^2 = 0.02), which means that large waves were not usually of short period that may be more destructive to mariculture facilities. Oceanic swell height estimates in the field were much less toward shore at 25 m depth, compared to further offshore at 50 m depth. This may be due to protection provided by Waadah Island, located immediately west of the study site.

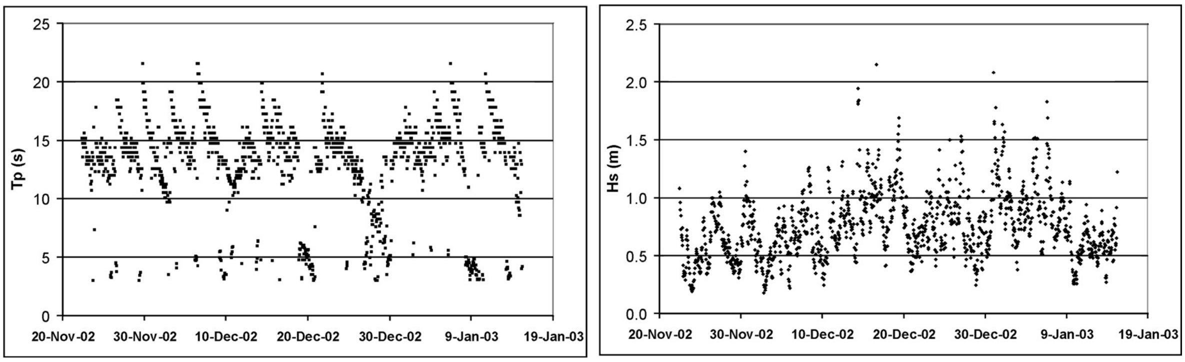

Fig. 3. Wave frequency (Tp, left) and significant wave height (Hs, right) offshore of Neah Bay during a two month period in the winter 2002-03.

Oceanic swell was also observed in the central Strait during our summer and fall field work but not in the eastern Strait on the same days. Significant wave height offshore of Whiskey Creek in a prior study in 1993 reached 3.6 m, but did not harm a prototype spar style offshore cage (Loverich and Croker 1997, Loverich and Forster 2000). Short frequency, choppy wind waves were relatively common during our field studies at all locations, particularly during afternoon hours. Modern offshore cage and anchoring systems should be able to survive all probable weather extremes at our study areas.

Water Temperature and Dissolved Oxygen Dynamics

The historical annual range of near-surface water temperatures in the Strait is approximately 7 to 12 C (e.g., Collias et al. 1974), more moderate than similar depths of north or central Puget Sound presently used for fish mariculture. The range is well suited to salmon and several other candidate marine fish species and is among the most moderate range of temperatures for all of temperate coastal waters of North America.

Dissolved oxygen concentrations in surface waters of the Strait follow previously documented seasonal and spatial cycles, peaking in late winter and declining during summer and early fall. In general, surface waters of the eastern Strait tend to have higher dissolved oxygen concentrations in the summer and fall than waters to the west, but at many times no consistent pattern is observable (Rensel and Forster 2002, 2003). We examined all available past surveys, studies and data reports, and could find no consistent trends within the central and western zones of the Strait at these times. Most prior studies were based on one year, once-per-month, multiple-day cruises or two year studies with less frequent cruises. Such monitoring is insufficient to describe the substantial change of dissolved oxygen that occurs in a few hours or a single tidal phase, as first noted by Herlinveaux and Tully (1961). Moreover, all prior published studies focused on deepwater areas, not in depths of 20 to 40 m as we did in our field studies.

A preferred approach to describe variability of dissolved oxygen in the Strait would have been to install moored instrument packages at several locations. But given the difficulties and cost of numerous such moorings, and the need to make repeated field observations of other factors, we chose two surrogate methods. The first was collection of vertical profiles of water quality during the potentially critical period of late summer and fall period in 2001 and 2002. The second utilized satellite sea surface temperature (SST) images, since it was shown that there is a strong positive correlation between near surface temperature and dissolved oxygen as described below. The former is reported in Rensel and Forster (2002, 2003) and indicated no significant differences among sampling locations. But the satellite SST approach yielded some interesting finds.

SST data was extracted from a transect located along the central longitudinal axis of the Strait between Neah Bay at the entrance to the Strait and Dungeness Bay at the eastern end of the Strait (Fig. 4d). In addition, the Strait was divided into 3 geographic regions (Western, Central, and Eastern Strait) for analysis purposes, and average transect temperatures for each region calculated from monthly composite satellite imagery.

Based on the SST satellite imagery analyzed, a persistent central Strait surface temperature reduction was noted for all months examined from May through October during 2001 and 2002. A persistent central Strait surface temperature reduction was noted for all months examined, when compared to the eastern and especially the western Strait (Figs, 4a and 4b). The feature is

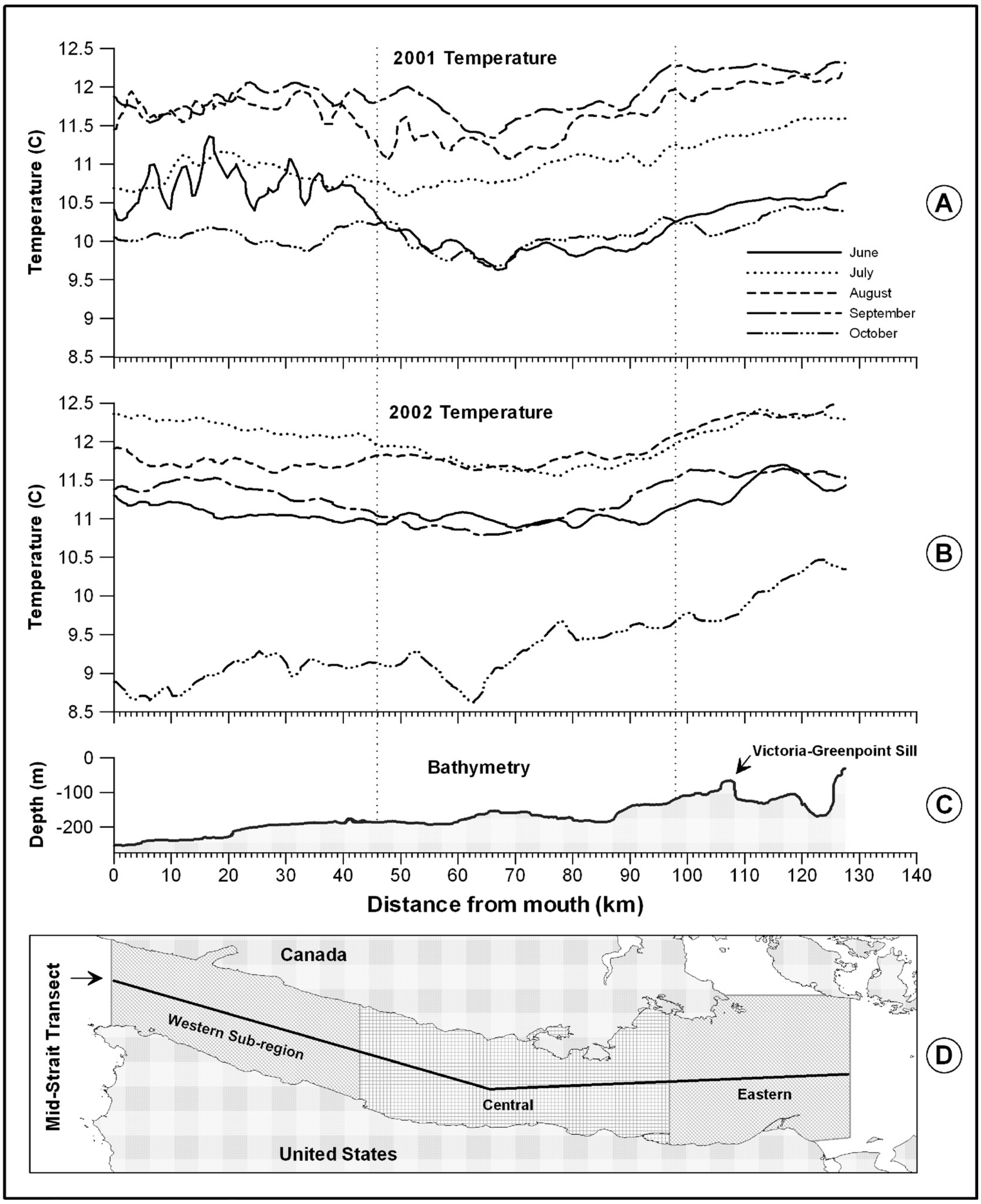

Fig. 4. AVHRR sea surface temperature imagery from the Strait of Juan de Fuca showing a lower temperature feature mid-Strait for a) 2001 and b) 2002 with c) bathymetry and d) transect sampled.

prominent in SST satellite imagery of the Strait and persistent to the extent of being visible in many daily and most weekly and monthly composites of the imagery (images not shown here due to color publication limitations). As much as a 1.5 to 3 ℃ temperature differential was observed in individual images, exceeding the 0.3 to 3 ℃ AVHRR SST error estimates noted above. In comparison, the eastern Strait had generally the highest SST results and the western Strait results were intermediate (Figs, 4a and 4b).

We compared temperature data from our field surveys using CTDs, previously discussed, to data from individual satellite images on the same days and same locations. There was an apparent lack of correlation between these data sources. There are several possible explanations for this. Satellite imagery provides an average temperature based on the pixel size of the imagery (1.1 km). A direct comparison between point data collected with the CTD and the average over a considerably larger area is necessarily going to yield differing results. In addition, the time differential between CTD data collection and satellite overpass was in some cases several hours, adding to the differential. Also, our field sampling locations were relatively close to shore where satellite imagery is less accurate due to interference from land. We would expect nearshore waters to be more variable and less vertically stratified due to more abrupt changes of bathymetry and the shoreline ruggedness that may enhance vertical mixing.

To our knowledge, there have been no prior published studies that have examined SST patterns in the Strait or mapped the extent of the surface temperature reduction we observed in the central Strait of Juan de Fuca persistently through the summer and fall months of our study in 2001 and 2002. The cause(s) of the temperature differential are unknown; however the bathymetry and cross channel profile of the central region may provide some insight. The single major bathymetric obstruction to deep flow in the Strait of Juan de Fuca is the Victoria-Green Point sill (Thomson 1994). The sill is located to the east of Ediz Hook in a region of slightly elevated surface-water temperatures (Fig. 4c). Circulation in the Strait is primarily estuarine, with cooler more saline oceanic water flowing inshore and eastward at depth, and warmer freshwater flowing seaward closer to the surface (Godin *et al.* 1980, Holbrook *et al* 1980, Thomson 1981). Supercritical turbulent flow over a shallow sill will cause deep water intrusions toward the surface during spring tides, particularly if density differences are minimal (Thomson 1994). Such phenomenon may be expected to vary on timescales similar or greater to a fortnightly schedule.

In addition to bathymetry, tidal cycle variation may influence the observed condition. Estuary to ocean exchange in the Strait is also thought to be modulated by tidal mixing and wind forcing that increases during neap versus spring tidal periods with greatest freshwater export during the neap tides (Griffin and LeBlond 1990). Monthly or bimonthly pulses of relatively warm fresh water have been documented traveling seaward from the western entry of the Strait (Hickey *et al.* 1991) although that particularly analysis was focused on the western entry to the Strait and adjacent oceanic waters off Vancouver Island. When we collated our data into neap vs. spring tide periods we did observe enhancement of the anomaly during spring tides and reduced intensity during neap tides, particularly during 2002 (the year with increased river flow).

Whatever the cause of the anomaly, apparent reduced water temperature in the central Strait may be biologically significant because as pointed out above, even a small temperature variation equates to a significant variation in dissolved oxygen. For example, using the 2001 regression ($y = 1.5186x - 8.3368$ where y = dissolved oxygen in mg/L and x is water temperatures in degrees C and $r = 0.92$) a decline of only one degree C water temperature from 10 to 9 ℃ results in a reduction of dissolved oxygen of 1.5 mg/L from 6.8 to 5.3 mg/L. For wild and particularly cultured fishes, these are significant changes.

Dissolved oxygen cycles have been observed at our reference station at Cypress Island, generally, but not exactly, correlated with the spring-neap cycles (Rensel and Forster 2003). In the case of the mid Strait anomaly, westward, estuarine flow of the surface layer may result in the shift of the surface water temperature anomaly to the west of the Green Point-Victoria Sill into the central Strait. Displacement of the feature so far to the west of the sill by tidal excursion may not be the only factor involved. Narrowing of the cross channel profile to the west of the sill and turbulence of high velocity flow near the south end of Vancouver Island may contribute by elevating the degree of vertical mixing. Occasional reversals of flow pattern allowing eastern transport of surface waters occur in winter and even summer (Thomson *et al.* 2004), although no low SST zone is persistently located to the east of the sill in the images we reviewed during the study periods of 2001 and 2002.

The low temperature anomaly we have observed and measured in the central Strait warrants further investigation. Other studies in the past (Herlinveaux and Tully 1961, Collias *et al.* 1974) have measured vertical diversion of deepwater toward the surface by the Victoria-Greenpoint sill particularly on the ebb tide, however such results are typically sectional views and do not indicate regular breaching of the surface layer. The feature is highlighted in satellite imagery because of the greater temporal and spatial coverage of a feature in context to the surrounding water masses and topography. The seasonal and interannual nature of this feature and linkages to other parameters such as dissolved oxygen and salinity should be investigated to further understand basic water quality conditions and effects on marine resources.

Phytoplankton and Harmful Algae

Few studies have documented the spatial or temporal occurrence of phytoplankton in the Strait. Fish mariculture interests have a special interest in phytoplankton and harmful algae as the former is a primary source of fish-sustaining dissolved oxygen in surface waters while the latter may cause occasional fish mortality (see Anderson *et al.* 2001 for case histories, Rensel and Whyte 2003 for overview of harmful algae and mariculture). In the Pacific Northwest, two genera of harmful algae have been involved in kills of wild or cultured fish.

Large blooms of the raphidophyte microflagellate *Heterosigma akashiwo* have caused occasional fish losses of mariculture fish and also wild fish in shallow bays. Blooms of *H. akashiwo* are somewhat predictable in north Puget Sound on a time scale of days, typically occurring during especially warm, sunny periods marked by neap tides and calm winds (Rensel 1995, Anderson *et al.* 2001). Second, large-bodied diatoms of the genus *Chaetoceros* (subgenus *Phaeoceros including C. concavicornis* and *C. convolutus*) are capable of killing wild and cultured fish at relatively low concentrations (Bell 1961, Kennedy *et al.* 1976, Rensel *et al.* 1989). In acute exposures, fish death is due to clogging the gill secondary lamellae with cells and excessive gill mucus production that interferes with respiration (Rensel 1993).

For the present study we collected 1 and 10 m water sample composites from all three offshore stations during our 2001 field studies. For comparison, samples at the same depths were also collected in the approximate centers of adjacent bays included Neah Bay, Port Angeles Harbor and Inner Dungeness Bay (1 and 5 m composite). Samples were preserved to 1% final concentration of formalin and later identified and enumerated using settled subsamples and an inverted microscope (Hasle 1978).

Overall, diatoms were represented by 55 species or taxonomic groups, dinoflagellates by 27 species and taxonomic groups, and microflagellates by 15 species, taxonomic groups or size classes. At the offshore stations, total cell counts were relatively low compared to the bays. Total diatom counts offshore averaged 1.2×10^5 cells L^{-1}, about an order of magnitude less than in the nearby bays that averaged 1.3×10^6 cells L^{-1}. A few *H. akashiwo* cells were seen in October 2001 at very low concentrations at offshore stations (mean 0.5×10^3 cells L^{-1}, fish death sometimes occurs at 75×10^3 cells L^{-1}). No cells were seen in Neah Bay or Port Angeles Harbor but 5×10^3 cells L^{-1} were observed from samples inside Dungeness Bay. A large bloom occurred in Puget Sound in late June 2006 after the completion of this study and the bloom was observed in the Strait out to the Pacific Ocean. In the eastern Strait the bloom was visible from an airplane survey very near the south shore, but not as prevalent offshore (K. Bright, pers. comm.).

Non-harmful species of *Chaetoceros* were dominant at the offshore stations composing 60.4% of the diatoms, with *C. socialis* more abundant than other diatoms. Inshore in the bays, non-harmful *Chaetoceros* composed 79.7% of the diatoms, followed by 7 species of *Thalassiosira* (9.9%) and Skeletonema costatum (5.3%). Approximately 2,000 cells L^{-1} of the harmful species Chaetoceros convolutus were counted from offshore of Neah Bay in early September but none were seen in additional samples from offshore of Clallam Bay at the same time. Such patchiness may be common with the harmful Chaetoceros in most cases. In vivo chlorophyll a measurements and laboratory extractions for offshore stations ranged from 1 to 4 $\mu g\ L^{-1}$.

Overall, we expect the offshore waters of the Strait to be more suited for fish mariculture in regard to less frequency of fish-killing harmful algae. Increased phytoplankton in the bays does afford somewhat higher dissolved oxygen concentrations during the summer and fall, but if certain species of marine fish are selected this may not be a primary consideration due to their lower respiratory requirements for oxygen.

Water Column Effects Modeling

We have developed a simulation model of marine fish farms to assess water column and benthic effects, as summarized at http://netviewer.usc.edu/aquamodel/index.html.

The model was imported into a marine, geographical information system called EASy (Environmental Analysis System www.runeasy.com developed by one of us, DAK), which provides a 4 dimensional framework (latitude, longitude, depth, and time) to run simulation models as well as to analyze field measurements as graphical and statistical outputs. Although several species of marine fish are candidates for future culture in the Strait, salmon were selected for this simulation since their physiology has been well studied, and they may be more sensitive to low dissolved oxygen. This salmon farm model is conveniently described in terms of 3 components: a growth and metabolic submodel of salmon within the farm, a plankton submodel that provides a description of the response to nutrient and oxygen perturbations caused by the farm and a 3 dimensional circulation submodel. The simplified version of the model is available on line for demonstration at http://netviewer.usc.edu/mariculture/mariculture.htm

The metabolic submodel of AquaModel is budgeted for the fate of carbon ingested by the fish; these include calculations of the rates of ingestion, egestion, respiration, and growth. Specifically, these rates are functions of the average weight of fish, the feed ration, the ambient temperature, oxygen concentration within the farm, and advective flow speed. The system of equations that describe rates of metabolism were obtained by fitting functions to the data found in the extensive literature on the growth and respiration of *Salmo salar* (Atlantic salmon) and *Onchorhynchus nerka* (sockeye) dealing with metabolic scope for activity including Fry (1947), Brett (1964, 1976), Brett *et al.* 1969, Brett and Zala (1975) and Smith, 1982.

Key features of the model are:

- The growth rate of the fish is determined by difference in the rate of assimilation of organic carbon (food) and the rate of respiration.
- The rate of carbon ingestion and assimilation is determined by a single most limiting factor: either the size of the fish, the temperature of the water, the food ration, the concentration of dissolved oxygen, or the swimming speed required of the fish within the farm.
- Because water temperature of Strait is slightly below the optimal temperature range for growth, the maximum growth rate of a 0.5 kg Atlantic salmon is calculated to be 0.01/ day, similar to that actually achieved in Puget Sound net pens for similar-sized Atlantic salmon and significantly below the maximum rate of 0.021 reported by Brett et al. (1969) for smaller sockeye salmon. In our model, the growth rate of the fish is reduced as conditions vary from near optimum.
- Respiration rates increase with swimming speed. Such increases in respiration cause decreases in growth rate when swimming speed exceeds the optimum range of ∼ 1 to 2 body lengths per second.

- The supply of oxygen to the fish is described mathematically as the product of the rate of flow of water across the gills (respiratory pumping at low speeds and ram ventilation at high speeds) and the ambient concentration of dissolved oxygen.
- The rate of oxygen consumption by the fish is linked to the rate of carbon dioxide production by a constant flux ratio of 1 mole O_2/mole CO_2, and the rate of nitrogen excretion by the fish is linked to the rate of carbon dioxide production by a constant flux ratio of 1 gm-at N/7 moles CO_2.

The ideal rate of flow for culturing Atlantic salmon is not known precisely, but is probably about 1 to 1.5 body lengths per second. In a literature review, Davison (1997) concluded that training at 1.5 body lengths per second (bl s^{-1}) or less improved growth rate and food conversion for many teleost species, but cited some exceptions in the literature showing conflicting information for Atlantic salmon and other species. It can also be concluded with certainty that above optimum swimming speeds do not result in better food conversion and growth and we would estimate that this means above 2 bl s^{-1} for larger (> 500 g) Atlantic salmon. Salmonids do not require a rest period for optimum growth, survival and food conversion, continual exercise results in better growth than intermittent swimming (e.g., Azuma 2001).

A plankton submodel describes the cycling by plankton of nitrogen and oxygen within each element of the array, both within the farm and the surrounding waters. This model is similar to the PZN models that have been published by Kiefer and Atkinson (1984) and Wroblewski, Sarmiento, and Flierl (1988). The "master" cycle describes the transforms of nitrogen between three compartments, inorganic nitrogen (consisting of the sum of concentrations for nitrate, nitrite and ammonia as well as urea as oxidized to nitrate), organic nitrogen in phytoplankton, and organic nitrogen in zooplankton.

The three biological transforms consist of:

- photosynthetic assimilation of inorganic nitrogen by phytoplankton which is a function of temperature light levels, DIN concentration, and dissolved oxygen concentration
- grazing by zooplankton on phytoplankton which is a function of temperature and concentrations of dissolve oxygen concentration, zooplankton, and phytoplankton
- excretion of DIN by zooplankton, which is solely a function of the concentration of zooplankton

It is assumed that all three compartments are transported by advective and turbulent flow as described above. The model displays predator-prey oscillations which dampen over time and reach a steady state. The default simulations for DIN, phytoplankton, and zooplankton stabilize at roughly 12 mg-at N-at m^{-3}, 2 mg-at N m^{-3}, and 3 mg-at N m^{-3}, respectively. In order to calculate the concentrations and rates of loss by respiration and production by photosynthesis, we have assumed a constant flux ratio of oxygen to nitrogen of 7 moles O_2 per gm-at N, consistent with the Redfield ratio. As indicated in the accompanying table, the inputs to this model consist of the time series of exchange coefficients produced by the circulation model, surface irradiance, and water temperature as well as concentrations of dissolved oxygen, dissolved inorganic nitrogen, cellular nitrogen in phytoplankton and zooplankton. Outputs of this model consist of a time series of the concentrations of dissolved inorganic nitrogen and oxygen, phytoplankton, and zooplankton.

The inputs to the fish farm model are the dimensions and location of the farm in the array, daily feed ration, the initial average weight and density of the fish, as well as the water temperature, and the time series of outputs from the circulation and plankton models. The outputs consist of a time series of the average rates of growth, nitrogen excretion, and respiration. The dispersion and BOD of egested, solid material (fish feces) is not considered since, as discussed above, the study areas are not depositional zone and the BOD is distributed widely in the deep layer or on the bottom.

The physical dimensions of the model are set by the user, and in our simulations the transport and transformations of variables was calculated for rectangular region or array that is aligned parallel to the coastline. The modeling domain is 10,000 meters in length, 2,500 meters in width, and 30 meters in depth. Figure 5 shows only the center of this domain. This region consists of a 3 dimensional array of rectangular elements each of which is 50 meters in length, 25 meters in width, and 5 meters in depth. The farm itself with dimensions of 50m x 25m x 10m occupies 2 of the elements, both in the center of the array with one at the surface and one immediately below. Water as well as the chemical and biological variables of the model are transported between adjacent elements of the array by advection and turbulent dispersion. The region is bounded by the air-water interface at its surface, by the 30 meter bottom, and by ambient waters along its 4 sides.

The circulation model is a simple finite element description of the movement of water and suspended and dissolved materials caused by advection and turbulent dispersion. Such circulation is described in terms of a box model in which flow occurs across 5 sides of those elements found at the surface and bottom and across all 6 sides of all other elements at intermediate depths deeper elements. Advective flow in the Strait is largely driven by semidiurnal tides that are oriented along the central axis of the array. Advection is constant with depth and occurs principally in the horizontal direction. We are able to run two types of simulation, one in which the time series of advective velocity was determined by the current meter records discussed above and another in which velocity was described by a sine function of 6-hour periodicity. Inputs to this model consist of the time series for advective flow, the depth of the surface mixed layer, and the dimensions of the region and location within the Strait. Outputs consist of exchange coefficients for advective and turbulent flow for all elements of the array.

Turbulent dispersion was parameterized as an exchange velocity whose value was some fraction of the speed of advective flow. Horizontal dispersion was assumed isotropic, thus the exchange coefficients of the 4 vertical sides of element were of the same value, 1/10th the advective velocity. However, vertical dispersion varied depending upon whether the element lies within the surface mixed layer or within the underlying water column. The vertical turbulent exchange velocity within the surface mixed layer was 10 times greater that its value in deeper waters, and the horizontal exchange velocity was 5 times greater than the vertical exchange velocity within the mixed layer. We have run simulations for winter conditions when the mixed layer extends to 30 meters, and summer conditions when the mixed layer extends only to 5 meters. The vertical exchange coefficients at the surface and the bottom of the water column are zero.

AquaModel provides several types of graphic displays of the dynamic 3-dimensional fields produced by the simulation model. These include plane 2-dimensional views of the waste plume produced by the farm at selected depths, 2-dimensional vertical transects or slices through the plume, 1-dimensional depth profiles at a given location, and time series plots of current speed, the mean growth rate of fish, and the concentration of any variable of within the farm.

Fig. 5 is a representative screen of selected outputs for the farm simulation model with oxygen selected as one of several available main screen views. It is a computational array for a virtual fish farm placed in surface waters offshore of Neah Bay at our study location.

The location of a virtual farm, which initially contains a concentration of 90 fish m^{-3} whose average weight is 0.5 kg, is marked by a central orange-colored rectangle. The resulting density of 45 kg m^{-3} is approximately triple the maximum loading achieved for S. salar in the past, but is used here intentionally to illustrate worst-case possible effects. Total biomass is set at about 0.6 metric tons for this single large pen simulation. Larger amounts of fish may be cultivated in an area, but presently offshore pens such as the Ocean Spar system are placed and moored separately, not in a series as with some nearshore pens. We show here a "snapshot" of the time series for a summer-time simulation during which the mixed layer is shallow, irradiance is sufficiently high to drive driving optimal rates of photosynthesis and grazing within near surface waters. The orange to green plume shows the horizontal distribution of waters with concentrations of dissolved oxygen that are below ambient concentrations. Such a plume is caused by the passage of water through the farm and subsequent mixing with surrounding waters. During a simulation the plume will spread toward the east during the flood tide and then recede and spread to the west during ebb tide. The magnitude of the oxygen reduction within the plumes will vary with tidal flow; highest during slack flow and lowest during peak tidal flow. These changes are complex and not only depend upon cumulative effects of the near-term history of advective and turbulent transport within the array but also depend upon the cumulative effects of the near-term response of the fish to the changing conditions.

The longitudinal red line is a transect placed (and easily moved) to measure conditions through the centerline of the plume; it yields a vertical transect of oxygen vs. depth that is shown in the lower left. At this time in the simulation the graph shows the concentration of oxygen is lowest within the pen which extends to a depth of 10 m. The other X-Y plots display a vertical profile of oxygen within the center of the farm (at the red dot, also moveable), the time series of the rate of advection (current velocity), and the instantaneous rate of growth of the fish over time.

Similar dynamic 3-dimensional views of the "farm's waste plume" may also be displayed concurrently for other variables of interest such as nitrogen, phytoplankton and zooplankton. Since the excretion of dissolved inorganic nitrogen and urea by the fish in the farm is proportional to the rate of consumption of oxygen, the "waste plume" is enriched in nitrogen, and its spatial distribution closely resembles that of the oxygen-deficit waters. The distribution of phytoplankton and zooplankton are unaffected by the farm as discussed below.

Analyses of Model Simulations

We have run the fish mariculture model for summer and winter conditions, and examined the results in terms of three key questions.

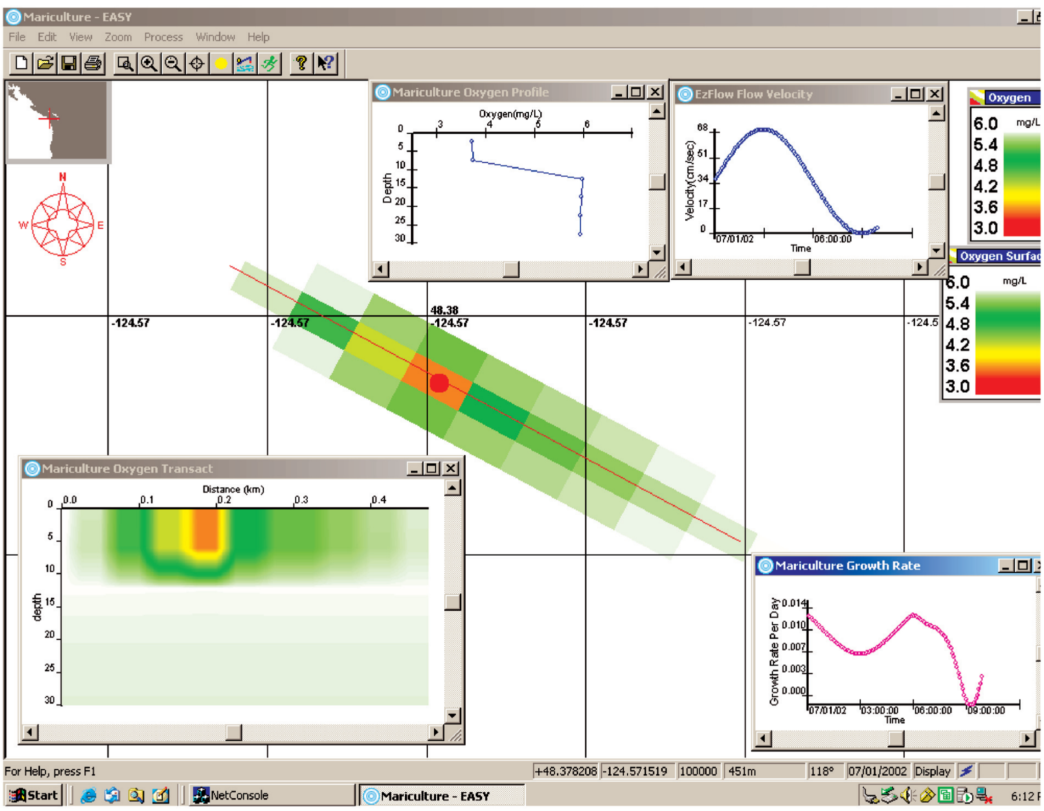

Fig. 5. Screen view of outputs from the simulation model showing just a few of the possible plots or profiles available for display and output to file. See text for explanation.

First, will the operation of a single farm stimulate algal blooms within the farm's nutrient enriched waste plume? Our simulations produced no phytoplankton enrichment much less a bloom. This result is easily explained by the fact that the ambient concentration of the limiting nutrient in the Strait, dissolved inorganic nitrogen, is much higher than the concentrations that are know to limit phytoplankton growth (Bowie et al. 1985, Rensel Associates and PTI Environmental 1991, Mackas and Harrison 1997). Even though the concentration of dissolved inorganic nitrogen is higher in the waste plume than in the surrounding waters, there is no increase in the growth rate of phytoplankton, because their growth rate is already nutrient saturated. In addition, because rates of turbulent dispersion in the Strait are high, the residence time of the phytoplankton within the waste plume is relatively short, a few minutes to less than a day.

The second question is: will the operation of a single farm form an oxygen-depleted waste plume that is of significant ecological concern? Our simulations showed that during times in the tidal cycle when flow is slow the concentrations of oxygen within the farm are much reduced, sufficient to temporarily reduce the metabolic rate of the fish. However, the simulation also revealed that the oxygen-deficit plume extended less than 50m downstream. Both the short duration of slack water and horizontal dispersion once flow accelerates limits the spatial extent of the plume. Many measurements up and downstream of commercial salmon farms by Rensel (1989) and more extensively by Heinig (1998, summarized by Normandeau Associates and Battelle 2003) indicate that reduction of downstream dissolved oxygen is extremely infrequent beyond about 5 m downstream, usually less than 0.1 mg/L at 30 m distance and non-existent at 100 m downstream. Such oxygen and nitrogen production data and horizontal dispersion measurements from drift objects are used for model validation, along with other types of data.

Third, is the growth rate of salmon within the farm significantly affected by environmental conditions? Our simulations indicate that the growth rate of the fish in the farm is sensitive to both ambient and operating conditions. Specifically, growth rates decline as ambient current velocities exceed ~60 cm s^{-3} for fish of the size modeled here. The metabolic cost of swimming against the increased current diminishes the reserves that support growth. Furthermore, growth rates decline when oxygen concentration declines within the farm falls. This occurs during slack water when water exchange within the farm is diminished, and the condition is exacerbated when the tidal flow reverses direction, thereby sweeping water from the oxygen-depleted waste plume through the farm. It is also exacerbated by decreases in the low concentrations of oxygen of ambient waters that occur during summer and early fall when cold, oxygen-depleted water is upwelled or advected to the surface of the Strait.

Discussion and Conclusions

This study indicates that the high energy study zone near the south shore of the Strait of Juan de Fuca is suitable for finfish mariculture with minimal or even no measurable adverse effects on benthic or plankton components. Dissolved nitrogen concentrations are constantly high, while standing stock of phytoplankton is relatively low. Light limitation and some grazing are the factors that limit phytoplankton growth in the Strait. Benthic impacts from fish mariculture facilities will be transient and limited in extent, as resuspension and fast transport rates will rapidly spread fish fecal matter for long distances downstream of the pens where it can be decomposed and biologically assimilated. AquaModel simulations provided a useful tool to examine probable effects.

Although environmental impacts discussed above should be very limited, rigorous conditions found in the Strait during storms will challenge fish culturists and demand use of offshore technology and methods. Operation, maintenance, grading and harvesting procedures in the cold waters of the Strait will demand innovation and careful consideration. The species of fish likely to be reared in such cages may include marine fish that have not been cultivated in offshore cages in the past. They may have an advantage over salmonids with regards to oxygen requirements (e.g., Sullivan and Smith 1982), but their physiological performance and stamina in high current conditions is not known in some cases. Creative configuration and arrays of pens to reduce surface currents or stocking of relatively large fish may be means to deal with elevated current velocity effects.

There are other factors besides those considered here in siting of fish mariculture in the coastal zone of the Strait. For example, the south shore of the central Strait has very prolific kelp beds that generate large rafts of floating, senescent material in the late summer and fall. Test versions of offshore cages placed offshore of Whiskey Creek in 1991 where able to withstand forces generated by this material impinging on the nets for long periods. Other regions of the south shore have much less kelp and resulting flotsam. Mariculture siting must also consider native Tribal fishing, sport fishing and commercial fish and shellfish areas, recreational and commercial navigation use, habitats of special significance, marine bird and marine mammal habitat and shoreline residents' view and aesthetic concerns. There is precedence for dealing with site-specific topics such as these. Washington State government has promulgated monitoring requirements, operation guidelines, a programmatic impact statement and 2 sets of NPDES permits (SAIC 1986, WDF 1990, WDOE 1996, WDOE 2002) to document impacts based on ten years of annual impact monitoring that led to strict impact limits and rules. This regulatory experience and set of rules can be applied to fish mariculture in the Strait of Juan de Fuca, an area that appears to have several notable advantages for marine fish mariculture.

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Direct payment system to promote the appropriate management of aquaculture grounds

Yasuji TAMAKI *

Abstract: Aquaculture occupies an important role in Japanese fisheries; it also plays various social, cultural and economic roles and functions other than food supply, but is becoming a problem in that leftover feed and excrement causes coastal environmental pollution. A subsidy system is already in place in the EU and USA to compensate for the decreased revenue and increased costs incurred by reducing environmental damage by agriculture. In this study, I consider a plan to apply a similar subsidy system to Japanese aquaculture.

Key words: direct payment system, aquaculture, multifunctionality

Materials and methods

Aquaculture is one of Japan's key industries: it provides a steady supply of various types of fish all nationwide. Aquaculture also has various social and cultural roles and functions. The financial state of aquaculture businesses, however, has been worsening for a number of reasons, including falling prices. The number of businesses is shrinking and their operators are aging. In this paper, I describe the current state of the Japanese aquaculture business through analysis of statistical data and case studies. Another point I discuss in the paper is pollution problems, including the damage caused to wild fishing grounds by uneaten fish food used in aquaculture and excrement of fish. I focus on the direct payment method applied in the agricultural field in some other countries and analyze it for its applicability to the Japanese aquaculture industry.

Results

(1) The current state of Japanese aquaculture

In 2002, Japanese marine aquaculture yielded 1,333,000 tons, worth 478.3 billion yen, and freshwater culture yielded 51,000 tons worth 43.8 billion yen. These account for 23% and 23%, respectively, of marine fisheries output and 45% and 42%, respectively, of freshwater fisheries output (Fig. 1). According to the national census of fisheries, the number of marine aquaculture businesses in 2003 was 23,068, 17% of the total number of fishing businesses. The number of freshwater aquaculturists was 4,495 in 2003.

For the production of major fish species in 2002 in marine aquaculture, the output of marine aquaculture was 162,000 tons for yellowtail and 72,000 tons for red sea bream; that of shellfish aquaculture was 272,000 tons for the common scallop and 221,000 tons for oysters; and that of seaweed aquaculture was 436,000 tons for laver, 54,000 tons for *Undaria* and 51,000 tons for *Laminaria* (Fig. 2). The output of laver and *Undaria* has been decreasing in the last few years. In inland water aquaculture, major fish species cultured include eel with an output of 21,000 tons, trout with 14,000 tons, carp with 9,000 tons, and sweetfish (ayu) with 7,000 tons (Fig. 3). The production of each of these is decreasing, with that of eels showing the steepest decline.

Concerning the financial condition of aquaculturists, the annual average fishery profits in 2002 was 7,745,000 yen for oysters, 7,654,000 yen for laver, 6,873,000 yen for common scallops, 4,725,000 yen for pearls, and 3,840,000 yen for *Undaria.* These

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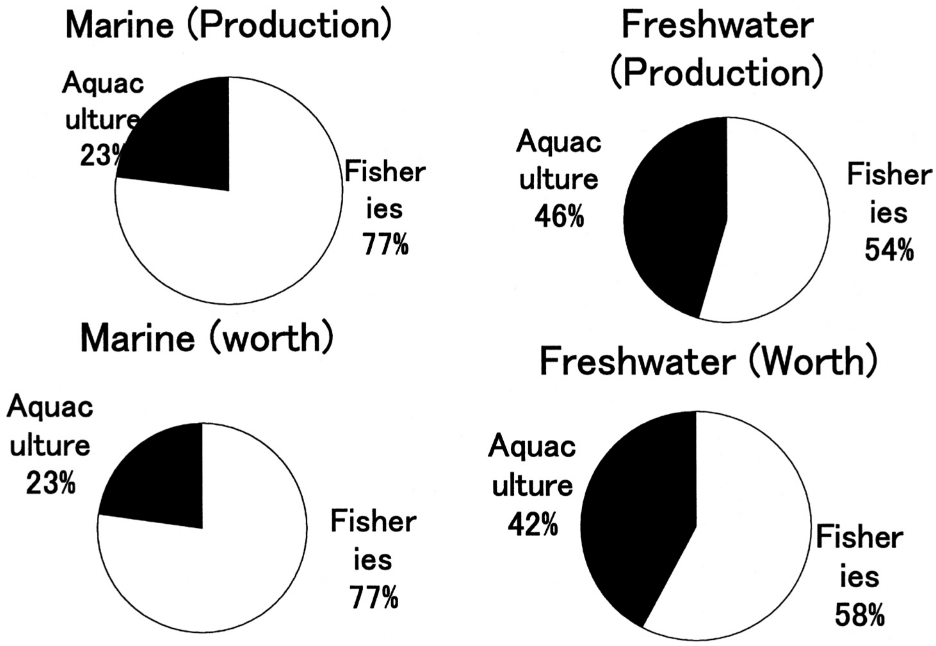

Fig. 1. Aquaculture proportion of the whole fisheries

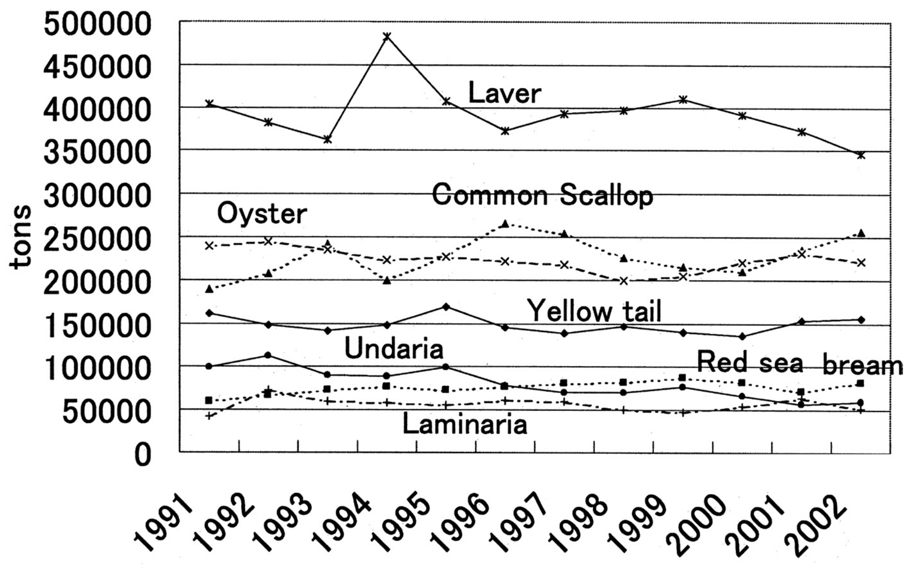

Fig. 2. Change of Marine Aquaculture Productuin

culturists earn more than the average profits for all fishing businesses. However, culturists of yellowtail (2,799,000 yen), sea bream (1,770,000 yen), and pearl oyster (792,000 yen), earn below the average of 2,871,000, evidence of their poor financial state (Fig. 4). Of 21,129 individual marine aquaculturists, 27%, or a little more than one-fourth, know who will take over the business when they retire. Of 3,457 individual freshwater aquaculturists, only 15% have successors (Fig. 5). Inland water aquaculturists

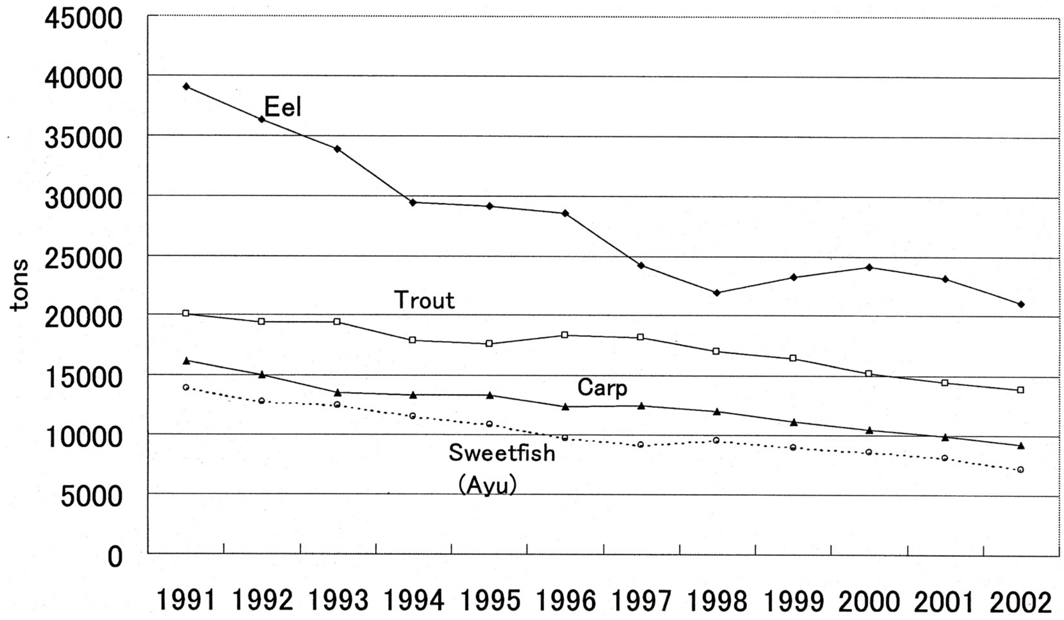

Fig. 3. Annual variation of Freshwater Aquaculture Production

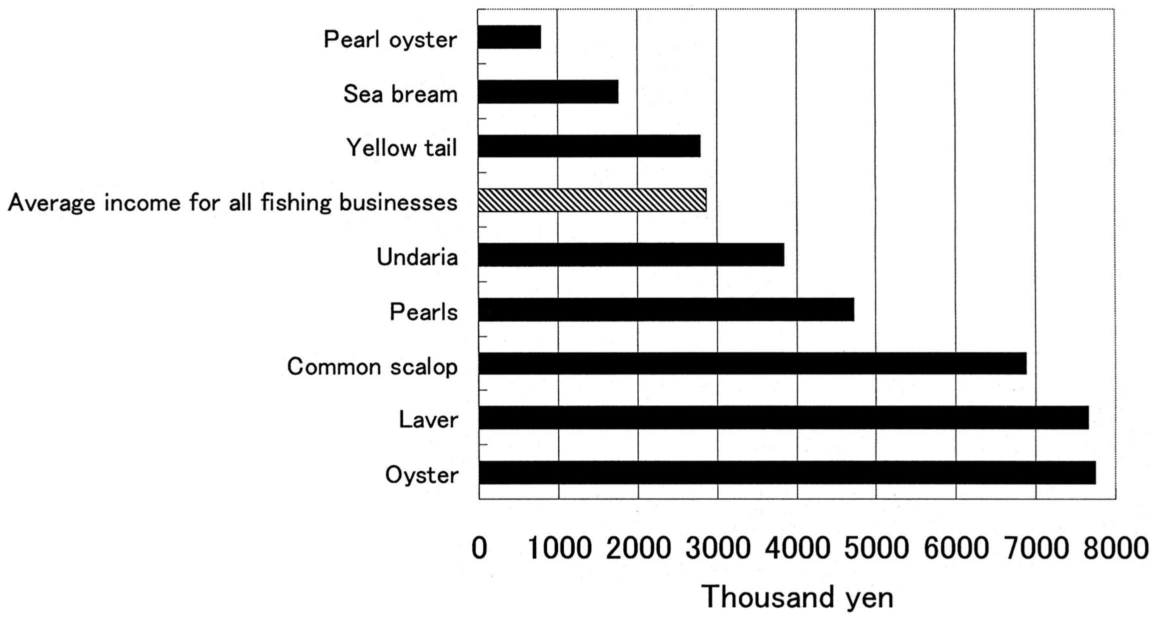

Fig. 4. Annual Average Profits of Aquaculture in 2002

are aging: 43% of male operators of inland water aquaculture are aged over 60. The majority of Japanese aquaculturists are small-scale operators dependent on family labor. The major cause of their financial deterioration is a drop in fish prices due to growing imports and the stagnant domestic economy. However hard each aquaculturist tries to improve their financial condition, it is not enough to bring about any significant improvement.

A comparison of the age constitution of male

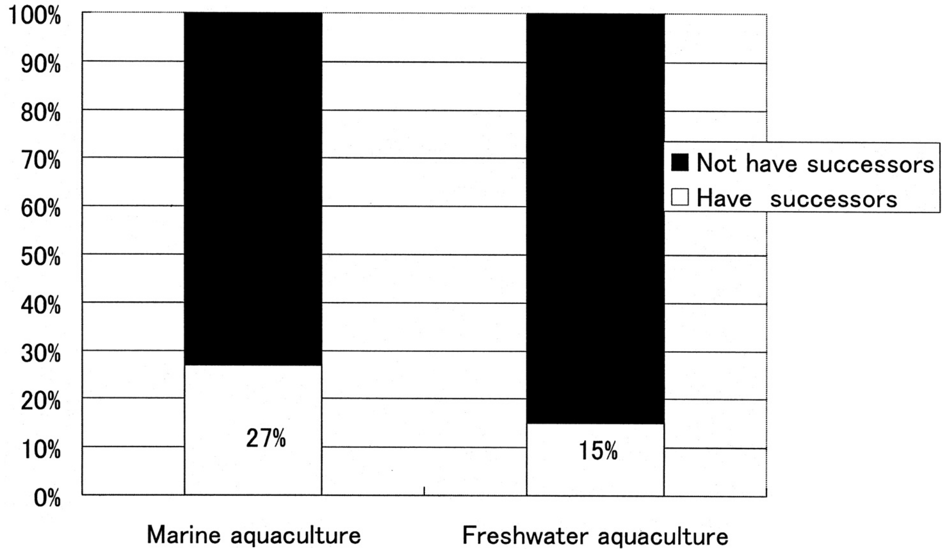

Fig. 5. Successors of Aquaculturist in 2003

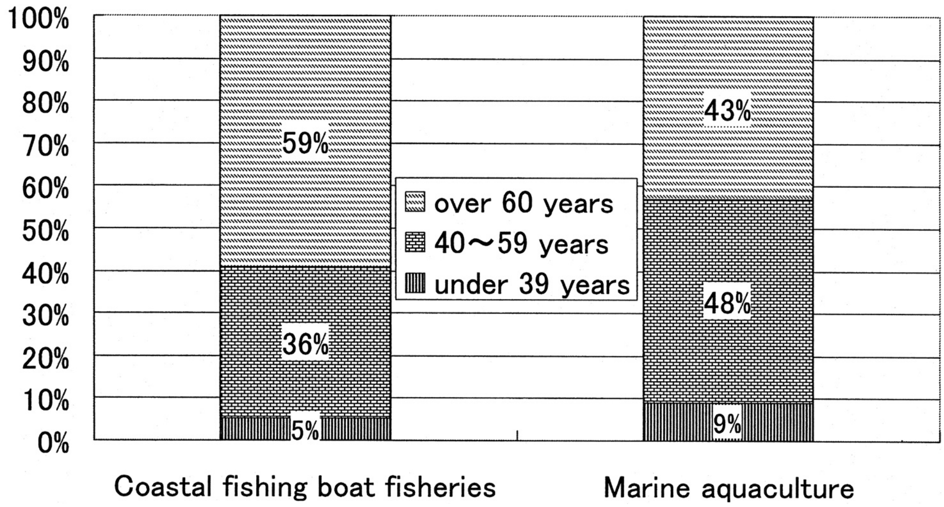

FIg. 6. A comparison of age construction of male fishery workers in 1998

fishery workers in 1998 between coastal fishing boat fisheries and aquaculture businesses, according to the census, shows 59% in fishing boat fisheries to be over 60 years of age, whereas fewer aquaculturists (43%) are over 60 (Fig. 6).

(2) The various roles and functions of aquaculture

Aquaculture has multifaceted functions in addition to the supply of fish. Each such function is explained below.

1) Food security

Unlike ordinary fishing, where fish are caught as a natural resource, aquaculture can reliably supply selected fish species with the help of appropriate technology. Some aquaculture seeds, such as yellowtail, oyster, or common scallop, may have to be taken from natural resources, but others, such as red sea beam, prawn, or laver, can be artificially

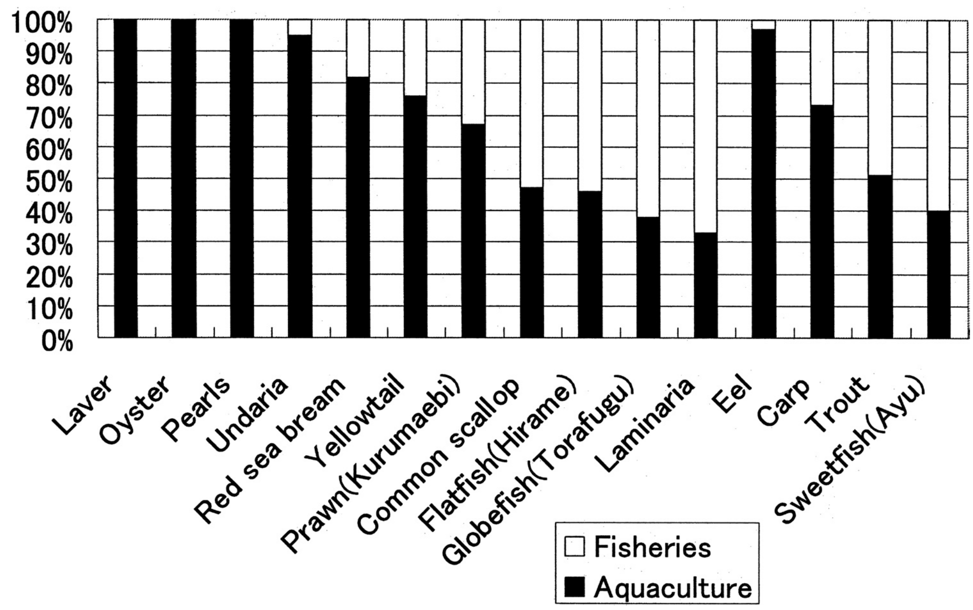

Fig. 7. Production Ration of Aquaculture in 2003

produced. Even when culturing natural seeds, taking special care of life stages at which fish seeds have a higher natural mortality rate can reduce the death ratio and minimize loss of resources.

In addition, aquaculture produces the types of fish that are particularly in demand. In fact, certain fish species are characterized by high production ratios, such as 100% for laver, oysters, and pearls; 95% for *Undaria*, 82% for red sea beam, 76% for yellowtail, 67% for prawn, 47% for common scallop, 46% for flatfish, 38% for globefish, and 33% for *Laminaria* as well as, in freshwater culture, 97% for eel, 73% for carp, 51% for trout, and 40% for sweetfish (ayu) (2003). There are many fish species that would disappear from the market or be in very short supply if it were not for aquaculture (Fig. 7). Given these circumstances, it is logical to conclude that aquaculture plays a major role in food security.

2) Environmental improvement (Table 1)

Seaweeds convert carbon dioxide in the seawater into oxygen through photosynthesis. They also prevent eutrophication of the seawater by immobilizing dissolved nitrogen and phosphorus. In cultured seaweed grounds, unlike natural seaweed grounds, we can recover most of the immobilized nitrogen and phosphor before these elements are eluted into the water. Seaweed also provides shelter to young fish and the larvae of many other creatures, contributing to biodiversity. In addition to the benefits obtained from seaweeds themselves, there are cases where the bamboo poles used in aquaculture for attachment of laver in the water can serve as substrates for the larvae of short-necked clams, promoting favorable growth of shellfish grounds. In waters where aquaculture facilities are set up, rafts and net pens used to aquaculture can also provide shelter for wild fish. It is impossible to carry out seine fishing or trawl netting in the same waters, thus promoting the preservation of marine resources. When filter-feeding marine species, such as bivalves and sea squirts, are cultured, they filter seawater and simultaneously reduce the organics in the water. Silver carp and white crucian carp produced in freshwater culture grow on phytoplankton and do not need to be fed, therefore reducing the pollution load on lakes. One kilogram of silver carp filter a cubic meter of water and eat 20 grams of phytoplankton daily (Ibaraki Prefecture, 1996).

3) Exchange between urban and fishing communities

Aquaculture promotes exchange between urban

Table 1. Environmental improvements by aquaculture

Aquaculture species	Example
Seaweeds	Convert carbon dioxide in the seawater into oxygen
	Immobilizing nitrogen and phosphor
	Provide shelter to young creatures
Bivalves and Sea squirts	Filter sea water and reduce organics in the water
Silver carp and White crucian carp	Filter sea water and reduce organics in the water
Aquaculture facilities (rafts and net pens)	Provide shelter for natural fish
	Stop the fisheries operation of natural resources and provide nursary ground

and fishing communities. For instance, a fisheries cooperative in Kagawa Prefecture has a cultured oyster ownership system in which consumers buy oysters at the seeding stage. Later, they are entitled to experience the harvesting of the grown oysters or have them directly delivered by delivery service. In this system, an aquaculture rope with some 70 oysters attached is sold at 2,200 yen. Orders for some 1000 ropes are received per year. They even come from outside the prefecture, such as from Okayama or Tokyo. This cooperative has also discovered that many consumers prefer to come to get the oysters themselves to having them delivered. Another fisheries cooperative is advertising for purchasers of oyster culture ropes, at 2,500 yen each, but only accept orders from consumers within the same prefecture. In 2000, they received some 500 orders. In Kagawa Prefecture, some culturists, including the said cooperative, have their own small restaurants that serve grilled oysters during the winter. A different cooperative offers "all the oysters you can eat" at 2500 yen per person and, in 1999, achieved sales of 10 million yen. In Kanagawa Prefecture, a "hands-on experience" program that offers a course in *Undaria* culture was provided for 100 groups at a fee of 3000 yen per group. Visitors took part in seeding of *Undaria* and studied the details of seaweed aquaculture and its environmental advantages, including how it purifies water. In November, they learned how to culture seaweed and in February experienced harvesting of the seaweed, took classes on the nutrients in *Undaria,* and learned how to use it in cooking. There are also exchange promotion programs in which elementary and junior high school students visit a fishing village as one of their school excursion destinations and take part in various events alongside the people of the village to gain a closer and more personal understanding of how they live. Since the culture grounds are close to the port and located in calmer waters than in the case of offshore fishing, programs that feature actual experience of aquaculture are very popular with city people as safe and accessible opportunities to experience this type of fishery. It is a valuable experience for young people to actually feed cultured fish species and see how shellfish species and seaweeds are cultured. They can actually see for themselves what the sea has to give them. Another example is "fishing ponds" using the sea surface in Mie and Hyogo Prefectures, or fresh water in other prefectures. These "fishing ponds" are very popular among angling fans, not to mention beginners and children who tend to be seasick in open waters, because they can experience fishing in a safe and unthreatening environment. Many of the fish caught from these ponds are cultured species. Aquaculturists facilitate exchanges between cities and fishing villages by stocking these ponds with fish and opening them to the public. Aquaculturists can also obtain a profit by selling fish for stocking the ponds. Oyster culture rafts are ideal nests for black sea bream, a popular fish with anglers, for their shade and the plants and animals that cling to them. In Ishikawa Prefecture, these rafts are

Table 2. Example of exhange between urban and fishing communities

Area	Example
Kagawa Prefecture	Cultured oyster ownership system
Kagawa Prefecture	Small restaurants that serve grilled cultured oyster
Kanagawa Prefecture	Experience of *Undaria* culture
Mie Prefecture and Hyougo Prefecture	Provide cultured fishes to "Fish ponds"
Ishikawa Prefecture	Oyster culture rafts are provided for sport fishing
Shimane Prefecture	Takes anglers aboard recreational fishing boats to the water near their aquaculture grounds
Freshwater	Fishrman's cooperative release cultured seeds for sport fishing
Fishing Village	School excursion

Table 3. Maintenance of traditions

Culture	Example
Maintain Japanese culinary traditions	Enjoy eel on specific days in summer
	Laver for Rice ball (Onigiri) and Rice roll (Norimaki)
	Sushi
Japanese garden	Fancy carp
Local festivals	Goldfish scooping

provided by some culturists for sport fishing. A fisheries cooperative in the Oki Islands, Shimane Pref., who know that large wild fish are attracted to their fish culture grounds to eat the fodder that leaks out, take anglers aboard recreational fishing boats to the waters near their aquaculture grounds. These anglers pay 10,000 yen per person for this experience and are allowed to take home up to three red sea bream. The cooperative had some 250 customers in five months in 2002. Freshwater fisherman's cooperative often release cultured seeds for sport fishing. According to the census, the total number of sport fishers in fresh water in 2003 was 7,770,000 (excluding those for bass). Thus, aquaculture plays numerous roles, including exchange between urban and fishing communities and provision of recreational opportunities to urban dwellers (Table 2).

4) Maintenance of traditions (Table 3)

I have already pointed out as one of the features of aquaculture that it provides types of fish that would run short if we relied exclusively on natural resources. Providing these fish also helps to keep alive Japanese culinary traditions. For example, it is a custom to eat eel on certain days in summer. Without aquaculture, however, the lack of eels would lead to this custom's disappearance. Red sea bream is very popular to the Japanese style wedding reception. Laver, indispensable for rice ball and sushi, is 100% supplied by aquaculture. Yellowtail, red sea bream, and common scallop are also essential materials for sushi and are supplied by aquaculture. Fancy carp (nishiki-goi) are an invaluable part of many Japanese gardens. Without aquaculture, "goldfish scooping," an essential and entertaining part of local festivals and a traditional festive pastime for children, would disappear. These aquarium fish species are also the products of aquaculture.

5) Formation and maintenance of local communities

Aquaculture needs calm waters and clear fresh water and is thus often conducted in places far from major cities. The economy of many such places relies entirely on fisheries and related industries. Aquaculture helps dilute the otherwise concentrated population in cities and settle people in remote areas by providing economic security. At the same time, it plays other associated roles, such as monitoring of national borders, preservation of national land and protection of the landscape.

(3) Pollution of fishing grounds by aquaculture

So far I have dealt with the bright side of aquaculture by discussing the originally intended and various roles and functions of aquaculture. However, it is also true that aquaculture causes problems. In aquaculture which involves feeding, residual fodder and feces are swept out of the grounds and cause pollution of neighboring waters and the sea floor. Even with shellfish culture, which requires no feeding, it is reported that feces and pseudofeces (rejected food particles embedded in mucus) tend to accumulate on the sea floor. Katsuhiko Ito (1994) compared the sediment in the water at the mouths of bays not used for aquaculture with those employed for shellfish (pearl) culture grounds and those with fish (red sea bream and yellowtail). The sediments were analyzed for total amount of sulfides, oxidation-reduction potential, total amount of organic carbon, total amount of nitrogen, and the content of pheo-pigment. The results showed sediments to be worst near fish culture grounds, followed by shellfish culture grounds and then non-cultured bays (Table 4). Red tides often occur in the waters with the most serious pollution, with the negative impact of such pollution affecting both cultured products and natural resources. Ito reported that toxic red tides, such as those comprising *Gymnodinium* or *Chattonella*, occur over wider areas in waters where fish culture is more common and extensive.

Table 4. Comparison of Bottom environment with Aquaculture grounds to non aquaculture grounds in Gokasyo-bay (average 1984-1985)

	Aquaculture		Non aquaculture ground
	Pearl	Fish	Bay-entrance
Total amount of sulfides (mg/g dried mud)	0.16	1.96	0.004
Eh (mV)	+172	−11	+323
Content of pheopigment (μg/g dried mud)	45.3	98.2	4.9
Total amount of organic carbon (mg/g dried mud)	20.4	23.4	2.1
Total amount of Nitrogen (mg/g dried mud)	2.51	3.53	0.37
Katsuhiko Ito (1994)			

Table 5. The Environmental Benefit Index of The Conservation Reserve Program (CRP) of USA

- Water quality (maximum 20 points)
- Wildlife (20)
- Land erosion (20)
- Reforestation (10)
- Desired rent

Eiichiro Nishizawa (2001)

(4) Direct payment methods used to support agriculture in some countries

Schemes based on the direct payment method assume that existing modes of agriculture impose loads on the environment, and are designed to compensate for the increased costs or loss of income that result from efforts to make agriculture more kind to the environment.

1) Agriculture in the USA

The Conservation Reserve Program (CRP) is a scheme created as part of the Food Security Act of 1985 to remove fragile and easily eroded farmland from production for 10 to 15 years. Instead, the United States Department of Agriculture (USDA) pays rent on the retired land and 50% of the cost incurred in maintaining the land's vegetation cover. As of October 2000, 13 million hectares of farmland, 8% of total farmland, was retired, with more than 80% of this retired land turned into grassland. A total of 290,000 farmers participated in the program. Rental payments made per year are $111.5 per hectare, and $4,800 per farm on average. Annual spending by the USDA on the CRP totaled $1.7 billion, accounting for half of environmental preservation spending. The rental payment and cost-share payment to be made by the USDA are determined based on a environmental benefit index calculated from the total sum of points for water quality (maximum 20 points), wildlife (20), land erosion (20), reforestation (10) and desired rent (Table 5) (Eiichirou Nishizawa, 2001).

2) Agriculture in the EU

EU agricultural environment programs provide subsidies to programs to limit the input amount of fertilizers and agricultural chemicals, maintenance of already reduced input, introduction and maintenance of organic farming, introduction of extensive production of plants, conversion of cultivated land to extensive grassland, reduction of rearing density of cows and sheep, introduction of farming methods necessary for preservation of the environment and preservation of the rural atmosphere and landscape, protection of rare or threatened breeds, maintenance and management of abandoned farmland or forests, retiring of farmland for over 20 years for protection of the biotope and water quality, and management of farmland for easier access by the general public and for recreational use (Table 6) (Keiichi Ishii, 2001). One example is the system of environment payments introduced in France. The overall programs in this system generally include reduction of input, conversion of farmland to grassland, long-term suspension of production, and reduction of rearing density, and, as local projects, preservation of biotopes and prevention of farmland decay. Grassland promotion grants are provided nationwide in France. The highest grant per contract is for reduction in rearing density, at about 27,000 francs (about 565,000 yen) (Table 7). In 1997, 1.9 billion francs were spent on the agricultural environment program. Of this amount, 1.63 billion francs were spent on the promotion of conversion to grassland. By type of operation, 69% of operators covered by the program were sheep and goat farmers and 55% were for beef farmers (Keiichi Ishii, 2001).

Discussion -Application of the direct payment method to Japanese aquaculture

Assuming that control of aquacultural activity based on a system using the direct payment method, as practiced outside Japan, would be effective in improving the fishing environment, I reviewed a potential form of direct payment system applicable to the Japanese case. If this method were introduced, it would run the risk of sending a clear message officially stating that aquaculture without control is an environmental threat. It is also important to set a certain standard that does not violate the polluter's responsibility principle and to make payments to aquaculturists who satisfy the standard.

Actions or efforts to reduce environmental loads include, for fish culture by feeding, reduction in rearing density, amount of fodder, and amount of chemicals; for shellfish culture without feeding, reduction in rearing density; and for aquaculture operated inland, installation of wastewater treatment facilities. Changing to fish species that have less environmental load is also a strategy for reducing environmental load. Reduction in CO_2 of vessels and processing machine such as laver molder. Changing floats of plastics and foam polystyrene to aluminum floats. Direct payment for doing this may be logically equivalent to the direct payment method used for

Table 6. EU Agricultural Environment Program

①Limit the input amount of fertilizers and agricultural chemicals, maintenance of already reduced input, introdudtion and maintenance of organic farming
②Introduction of extensive production of plants, conversion of cultivated land to extensive grassland
③Reduction of rearing density of cows and sheep
④Introduction of farming methods necessary for preservation of the environment and preser-vation of the rural atmosphere and landscape, protection of rare or threatened breeds
⑤Maintenance and management of abandoned farmland or forests
⑥Retiring of farmland for over 20 years for protection of the biotope and water quality
⑦Management of farmland for easier access by the generalpublic and for recreational use

Table 7. The system of environment payments introduced in France

①Overall programs
- Reduction of input (422)
- Conversion of farmland to grassland (236)
- Long-term suspension of production (Biotopes (302), Water maintenance (247))
- Reduction of rearing density (565)
- Protection of rare or threatened breeds (52)
- Switch to organic farming (485)

②Local projects
- Preservation of biotopes (242)
- Prevention of farmland decay (226)
- Prevent a risk of a fire (427)
- Water maintenance (349)

③Provided nationwide in France
- Grassland promotion grants (283)

( ) means average grant per one contract (Thousand yen)
Keiichi Ishi (2001)

Table 8. Actions or efforts to reduce environmental loads

Type	Example
Fish aquaculture by feeding	Reduction in rearing density, amount of fodder, amount of chemicals
	Change to seaweed aquaculture
Shellfish aquaculture without feeding	Reduction in rearing density
	Change to seaweed aquaculture
Inland water aquaculture	Installation of wastewater treatment facilities
Aquaculture	Reduction in CO2 of vessels and processing machine
	Changing floats of plastics and foam polystyrene to aluminum

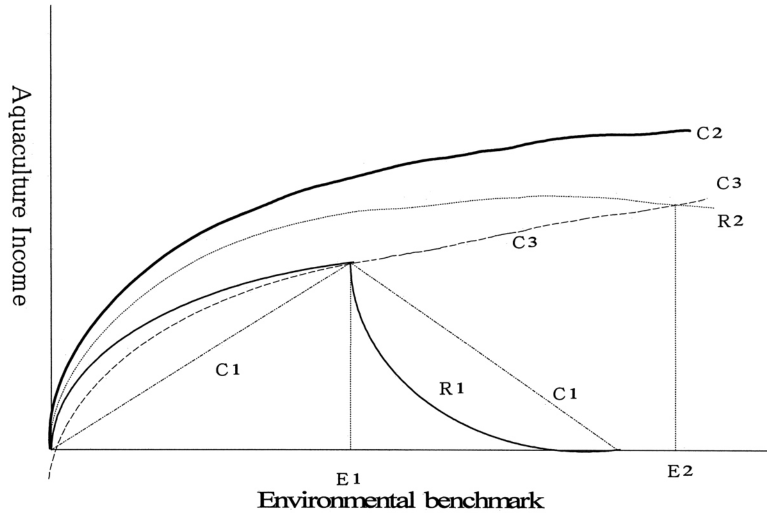

Fig. 8. The Schematic Diagram Showing the Relationship between the Environmental benchmark and Aquaculture Income

agriculture in some other countries. For example, it is considered worthwhile to plan coordination with fishing ground improvement plans in the Law to Ensure Sustainable Aquacultural Production (Table 8).

According to the schematic diagram showing the relationship between the environmental benchmark and aquaculture income shown here, for R1, the production curve of ordinary aquaculture, production increases with the rise of the environmental benchmark until reaching a certain point E1. But after E1, it is necessary to reduce production to maintain the environmental benchmark. For C1, the cost curve of ordinary aquaculture, past E1, costs are reduced due to production control, but the balance turns negative due to a large reduction in income. R2 is production curve of environmentally frindly aquaculturists, increase of production does not give big influence to environmental benchmark. C2 is the cost curve of environmentally friendly aquaculturists, who have a minus balance, since the cost is greater than for ordinary aquaculturists. On the other hand, C3 is the cost curve of an environmentally friendly aquaculturist who received a grant for cost reduction efforts. They make a profit until the break-even point at E2. E2 is a higher environmental benchmark than E1 (Fig. 8).

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Nutrient uptake by *Undaria undarioides* (Yendo) Okamura and application as an algal partner of fish-alga integrated culture

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Abstract : Nitrogen (N) and phosphorus (P) budgets in a fish-alga integrated culture were studied using an edible kelp, *Undaria undarioides* and the red sea bream *Pagrus major* in Tanabe Bay, Japan. The kelp was cultured on one rope (16 m in length) surrounding a fish culture cage (3 x 3 x 3 m) to reduce the loads of fish discharge. From 2002 December to 2003 March, 260 young red sea breams (172.7 g in average), were cultured in the cage by feeding 18.4 kg of artificial compounds containing 1435 g nitrogen and 282 g of phosphorus. At the end, 8.3 kg of fish growth was obtained; 243 g (16.9 % of the given feed) of N and 71 g (25.2 %) of P were stored in the fish bodies. During the culture, kelp absorbed N and P at estimated rates of 3.11 μg atm/wet g/hr and 0.16 μg atm/wet g/hr, yielding 161 kg of commercial size on the rope. The total amounts of N and P absorbed by kelp corresponded to 40.5 % and 25.9 % of those in given food, respectively. This is the first report of the total N and P budgets in a fish-alga integrated culture in Japan.

Introduction

An edible kelp, *Undaria undarioides* (Laminariales, Alariaceae), which is close to a widely distributed and utilized species, *U. pinnatifida*, is localized in southern parts of warm temperate in Japan (Okamura 1915). As the unique kelp is commercially important as a local high-priced food, culture has been attempted in southern coasts of Wakayama Prefecture (Kimura & Notoya 1996). On the other hand, cultures of red sea bream, *Pagrus major* have been popular in these areas (Uede & Takeuchi 2004). As the fish cultures are localized in inner bays, where seawater exchanges are limited, lords of nitrogen and phosphorus discharged from fish cultures, including excretion and defecation from fish, dissolution from residual feeds or re-suspension from the bottom sediments, are becoming problematic (Uede & Takeuchi 2004). These nitrogen and phosphorus, however, are essential nutrients for the growth of seaweed. Therefore, enriched seawater stagnating around fish culture is highly expectant for cultures of commercial seaweeds including *U. undarioides,* particularly in the form of fish-alga integrated culture. Although integrated cultures are worldwide concerns (ex. Troell *et al.* 2003, Neori *et al.* 2004), the combination of red sea bream and *Undaria* species is limited to Kitadai & Kadowaki (2004 b), in which nutrient uptake by *U. pinnatifida* was determined. In the present study, the authors reported the nitrogen and phosphorus budget in a red sea bream-*U. undarioides* integrated culture.

Materials and Methods

Culture of red sea bream:

Red sea bream was cultured in the Mera Cove of Tanabe City in Wakayama Prefecture (Fig.1) from 2002 Dec. 14 to 2003 Mar. 12. A total of 260 fish of a mean body weight of 172.7 g were kept in a cage (3x3x3m) fixed at the sea surface and satiated by feeding soft-dry pellet (SP)(See Table 1) 4 days (in evenings) a week. This type of feed was used to minimize the load to the ambient water. The total weights of fish were determined at the beginning

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and the end after 89 days culture. The seawater temperature ranged between 12.2 and 19.2 ℃ during the culture.

Estimations of nitrogen and phosphorus from red sea bream:

In analysis of fish body composition, 5 fish samples were taken at the beginning of the experiment, and whole fish bodies were used after slicing. Water, protein, lipid, ash and phosphorus contents were determined using methods of the normative thermal desiccation, quantitative nitrogen desiccation, Soxhlet extraction, direct ashing and vanado-molybdic acid absorbance, respectively. Nitrogen or phosphorus loads discharged from cultured fish were estimated by subtracting the value of each component obtained from the harvested fish bodies from that obtained from the total weight of given feed. Nitrogen was assumed to be 16 % of proteins contained in the feed and the fish bodies.

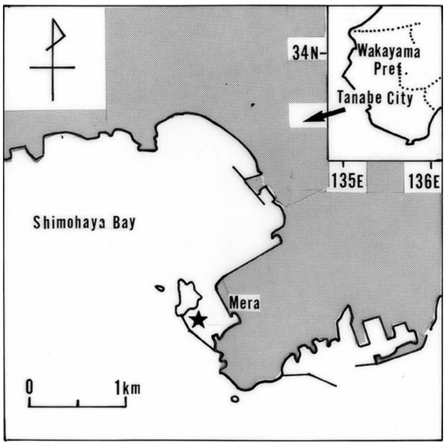

Fig. 1. Map showing the location for cultivation of red sea bream and *Undaria undarioides* (Yendo) at Shimohaya Bay in Wakayama Prefecture. (★) The place which examined.

Table 1. Composition of the experimental a diet

Ingredients		
Jack mackerel meal	50	%
Defatted soybean meal	5	
Corn gluten meal	5	
Wheat flour	17	
Pregelatinized starch	5	
Pollock liver oil	15	
P-free mineral mix	1	
Vitamin premixture	2	

Diet of nutrient content		
Moisture	2.1	%
Crude protein	49.0	
Crude fat	20.4	
Crude ash	9.2	
Phosphorus	1.54	

Culture of kelp:

Juveniles of *U. undarioides*, produced in Fish Farming Laboratory Fisheries Experimental Station, Wakayama Research Center of Agriculture, Forestry and Fisheries on 2002 Nov. 28, were kept in the form of square (4 × 4 m) at a depth of 1 m around the cage of *P. major* cultures using a rope of 16 m long. The strings of 30 mm long, on which juveniles attached, were stuck into the rope (18 mm in diameter) at 20 cm intervals, resulting in sticking out of each string end by 6 mm long on both sides of the rope. Namely, a total of 80 strings with two ends were set around the cage. As the growth of *U. undarioides* varied, all of the thalli growing on one end of a string (called unit string hereafter) were collected from 5 sites of the rope. The mean weight and number of kelp per half-side string was estimated after removing excess water. The samplings were conducted on 2002 Dec 28, 2003 Jan. 6, 20, 30, Feb. 10, 21 and Mar. 14. On the last day, although some of thalli were matured, matured ones were eliminated.

Estimations of nitrogen and phosphorus absorbance by cultured kelp:

Nitrogen and phosphorus levels incorporated into the kelp from sea water were estimated from weight gain of the thalli and their ratios of water, total nitrogen and total phosphorus contents. Total nitrogen and total phosphorus were determined by Kjeldhal method and vanado-molybdenum absorbance method, respectively.

RESULTS

Estimated nitrogen and phosphorus contents in red sea bream culture: The growth and analytical data (including data of feed) of red sea bream are shown in Table 2 and Table 3, respectively. The total weight of given feed was as low as 18.3 kg for 89-day period, yielding weight gain of 8.3 kg in fish bodies. The nitrogen and phosphorus contained in

Table 2. Results of red sea bream feeding with the EP-pellet in the 3×3×3m net cage from Dec.14 to Mar.12

No. of fish	Average body fish(g)		Daily feed intake(%)	Weight gain(g)A	Growth rate(%)	Amount of diets(g) B	Feed efficiency	Mortality (%)
	Initial	Final						
260	172.7	205.3	0.42	8,297	1.19	18,300	45.3	1.15

Table 3. Composition of the Whole body of red sea bream

		Diet	Body
Moisture	%	2.1	67.3
Crude protein	%	49.0	18.3
Crude fat	%	20.4	9.6
Crude ash	%	9.2	4.7
Phosphorus	%	1.54	0.85

the given feed were 1,435 g and 282 g, respectively. Nitrogen and phosphorus pooled in the harvested fish bodies were 243 g (cumulative rate: 16.9 %) and 71 g (cumulative rate: 25.2 %), respectively. Using these data, the nitrogen and phosphorus loads to the ambient water were calculated as 1,192 g (83.1 %) and 212 g (74.8 %), respectively.

Estimated nitrogen and phosphorus absorbance by the cultured kelp:

Changes in weight, height and number of the kelp per unit string were shown in Fig. 2. The kelp grew rapidly between Jan. 6 and Mar. 14 after a lag phase lasting 40 days, recording final biomass of 1,007 g per unit string or 37.3 g per thallus. As 5 strings were stuck into 1 m of rope and each sample was collected from one end of each string, the yield was estimated as 10 kg/m (≒ 1,007 kg × 2 x 5) or a total of 161 kg on the rope (16 m) around the cage of fish culture.

Composition of the kelp blade was shown in Table 4. The nitrogen and phosphorus incorporated through cultivation were 483 g and 54.7 g, respectively. Therefore, 40.5 % and 25.9 % of the nitrogen and phosphorus loads the ambient water (1,192 g and 211 g, see above) were assimilated by the cultured kelp, respectively. The budgets of nitrogen and phosphorus in the present integrated culture were summarized in Fig. 3. Using the growth data, the *in situ* uptake rates of nitrogen and phosphorus by the kelps were calculated as 2.34 μg atm/wet g/hr and 0.26 μg atm/wet g/hr, respectively.

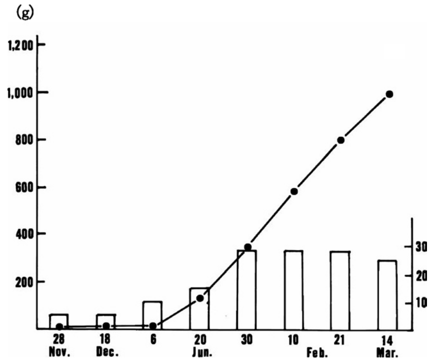

Fig. 2. Changes in the weight (—●—) per culture unit string and number (□) of blade *Undaria underioides.*

Discussion

In the present study, we could obtain commercial-sized edible kelp *Undairia undarioides* by utilizing the nitrogen and phosphorus discharged from a red sea bream culture, although the experiment is limited in winter, when growth of the kelp is high (Kimura & Notoya 1996) but that of red sea bream *P. major* is low because of low feeding activity in low temperatures (Fukusho 1986). For the warmer seasons, *Sargassum fusiformes* and *Ulva pertusa* (Kimura & Tanaka 2004) are now on trial as the candidates for the algal partners.

In the previous studies on red sea bream and seaweed integrated culture, *U. pertusa* (Hirata *et al.* 1993, Kitadai & Kadowaki 2004a), *Laminaria japonica* (Kitadai & Kadowaki 2003) or *U. pinnatifida* (Kitadai & Kadowaki 2004b) was used as algal partners. In these studies, however, only absorption of nutrients by algae was paid attention without demonstrating any data on nutritional input and

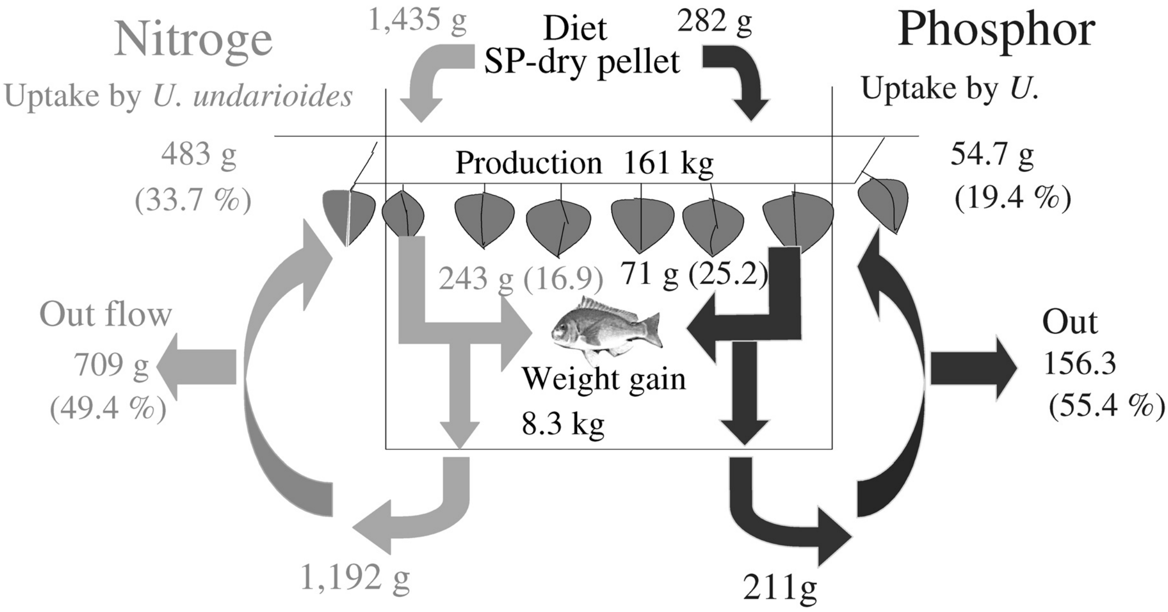

Fig. 3. Circulation of nitrogen and phosphorus at the red sea bream with *Undaria undariodes* culture.

Table 4. Composition of the blade of *Undaria undarioides*

Moisture	g/100g	90.3
Total amount of nitrogen	g/100g	0.3
Total amount of phosphorus	mg/100g	34

output from red sea bream culture. Therefore, this is the first report that showed the total nutrient budgets in the red sea bream-alga integrated culture. Furthermore, we could provide several benefits of the integrated system other than the above moral benefit as followings.

First of all is the depth merit. The depth of *U. undarioides* culture in the present integrated system (1 m) was shallower than depths (2 to 8 m) of its natural habitats (Okamura 1915; Kimura 1995). However, Kimura and Notoya (1996) revealed that the growth of the cultured kelp was faster at depths of 0.5 and 1.5m than at a depth of 2.5m. In addition, the subsurface culture of the kelp also gives spatial refuge to juvenile kelps because browsing by the herbivorous fish, *Siganus fuscens* is the most significant factor causing the reduction of the kelp at depths from 2.5 to 7 m from November to February, in which the water temperatures are enough high (>16 ℃) for its browsing (Kimura 1995). Thus the culture depth of *U. undarioides* is well coincidence with that of the red sea bream culture usually practiced near sea surface (Fukusho 1986).

The present integrated system could reduce equipments for *U. undarioides* culture such as anchors and floats by using a framework of the red sea bream culture, resulting in the decrease of cost of equipment by ca 90 % (ca 200,000 yen) comparing with the case of non-integrated culture of the kelp. Additional income (ca 40,000 yen in the present case) was also available for the culturists by selling the kelp at the price of 350 yen/wet kg. These economical benefits substantially support the introduction of integrated cultures by raising the motivation of fishermen.

Acknowledgement

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Growth, nitrogen and phosphorous uptake rates and O_2 production rate of seaweeds cultured on coastal fish farms

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Abstract To improve the water quality in coastal fish farms throughout year, we cultured *Undaria pinnatifida* at 12-19℃, *Laminaria japonica* at 13-26℃, and *Ulva pertusa* at 17-28℃ in the Yatsushiro Sea. The growth, N and P uptake rates and O_2 production rate of seaweeds were estimated. The growth of the seaweeds cultured were identified and measured. Each of the seaweeds cultured was collected monthly and analyzed for N and P contents. The observed N and P uptake rates per the blade and thallus area ($P_{N,P}$, mg N,P/m_s^2/day) of each seaweed were calculated by the following formula: $P_{N,P} = (C_{N,Pt} - C_{N,P0}) \cdot \alpha / t$, where $C_{N,P0}$ is the N and P contents at the start of the experiment (mg N,P/g dry), $C_{N,Pt}$ is the N and P contents day t (mg N,P/g dry), α is the dry weight per the blade and thallus area, and t is the cultivation days. The calculated N and P uptake rates of the seaweeds cultured were estimated from the dissolved inorganic nutrients concentrations, irradiance, and water temperature characteristics found at the fish farms. The O_2 production rates of the seaweeds were measured by the Winkler's method used light and dark oxygen bottles on fine day in the fish farm. The allowable volumes of seaweeds cultured for N uptake to N load in fish farming area, and for O_2 production to O_2 consumption by a fish cultured in cage were estimated by using the maximum N uptake rate and the maximum O_2 production values, respectively.

Key words : seaweeds, coastal fish farm, N and P uptake rates, O_2 production rate, growth

Introduction

Today, biological water purification strategies are required to solve anoxic water and prevent eutrophication, aiming to establish sustainable aquaculture that can be produced on coastal fish farms (Kadowaki, 2001). Seaweed cultivation results in dissolved nitrogen and phosphorus that can be uptaken to supply oxygen for cultivation on coastal fish farms. For an entire year we cultured seaweed on coastal fish farms, and the nitrogen (N) and the phosphorus (P) uptake rates of seaweed were fixed by the environmental factors of the dissolved inorganic nutrients, the irradiance, and the water temperature. The oxygen (O_2) production rate of the seaweed was fixed by the environmental factors of the dissolved inorganic nutrients. Furthermore, the minimum cultivation scales of seaweed to reduce the N load and improve the O_2 environment were estimated by the results of the N uptake rate and the O_2 production rate of seaweeds.

Materials and Methods

Seaweeds cultivation were carried out at stations A-E in coastal fish farms in the Yatsushiro Sea (Fig.1). During the investigation period the water temperature (WT) and the dissolved oxygen (DO) concentration of each station were recorded at 3 meter under the surface every three hours. Dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations were analyzed once a week (Strickland and Parsons, 1972). During the experiment period, downward irradiance

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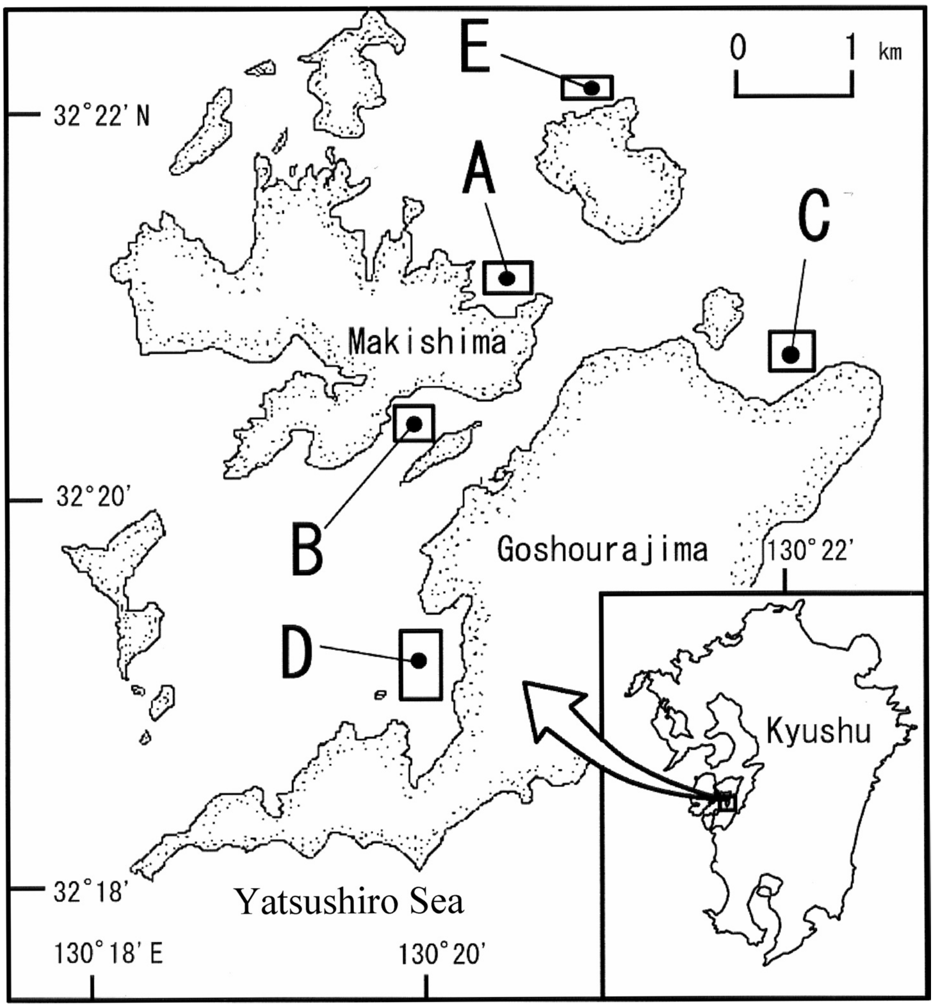
was automatically recorded under the surface at the 1.3 meter and 2.0 meter depths every hour with a photon meter (LI-COR model 190SA). We cultured *Laminaria japonica* from December 2000 to July 2001, *Undaria pinnatifida* from November 2002 to May 2003, and *Ulva pertusa* from August 2002 to November 2002. *L. japonica* and *U. pinnatifida* were cultivated under the surface at the 1-4 meter layer, and *U. pertusa* was cultivated under the surface at the 0.5-8 meter layer. *L. japonica* and *U. pinnatifida* of blade length (BL), and the *U. pertusa* of the thallus area (TA) which were identified, were measured twice a month. The area, the weight, and the N and P contents in the seaweed were measured every month, and the analyzed N and P uptake rates were also measured. On fine days, the O_2 production ($P'c$) and consumption ($R'c$) rates per chlorophyll-a of the seaweed were measured between 10 a.m. and 2 p.m for 4 hours on a fish farm. The suspended depth of light and dark bottles was 2 meter at *L. japonica* and *U. pinnatifida*, and 0.5 m depth at *U. pertusa*. DO concentration was analyzed by Winkler's method.

The relationship between N and P uptake rates ($P_{N,P}$) per seaweed area and the $P'c$, DIN, and DIP concentrations were elucidated by Michaelis-Menten's formula. Maximum N and P uptake rates ($Pm_{N,P}$), maximum O_2 production rate ($P'cm$), and Michaelis-Menten's constants ($K_{N,P}$) of DIN and DIP concentration were calculated (Kitadai and Kadowaki, 2003; 2004a; 2004b). The relationship between $P_{N,P}$ and downward irradiance was analyzed

Fig. 1. Map showing the cultured sites of seaweeds at stations A-E of Goshoura coastal fish farms in the Yatsushiro Sea



by the Steel formula (Steel, 1962) to calculate the saturation irradiance (*Im*) to $Pm_{N,P}$. The relationship between $P_{N,P}$ and water temperature was analyzed by the Allometry formula (Kadowaki and Tanaka, 1994) to calculate the temperature coefficient (Q_{01}).

The densities of seaweeds cultured per fish farm area necessary to uptake the N load by the *Seriola quinqueradiata* culture were calculated. In addition, the cultivation weights of seaweeds necessary for oxygen consumption per a *S. quinqueradiata* cultured and the cultivation densities of seaweeds to oxygen consumption per cage volume of *S. quinqueradiata* cultured were provisionally calculated.

Results

Cultivation environment

The WT and DO concentration during the cultivation period were 12-28 ℃ and 5.7-10.7 mg/l at stations A-E, respectively. DIN and DIP concentrations ranged between 31-150 μg N/l and 7.0-27 μg P/l, respectively. DIN/DIP ranged from 3.1 to 8.4. The mean downward irradiance value (±SD) in the 2 meter depth for the investigation period was 650 ± 74 μ mol/m_f^2/s.

Growth of seaweeds

The maximum BL of *L. japonica* and *U. pinnatifida* reached 250 cm and 182 cm at the 2 meter depth, and their maximum growth rates were 3.0 cm/day and 4.2 cm/day, respectively. The maximum TA of *U. pertusa* reached 640 cm^2 at the 0.5 meter depth, and the maximum growth rate was 41 cm^2/day (Table.1).

N and P uptake rates of seaweeds

The Pm_N of *L. japonica, U. pinnatifida,* and *U. pertusa* were 2.9, 3.1, and 3.6 mg N/m_s^2/day, and the Pm_P were 0.43, 0.54, and 0.19 mg P/m_s^2/day, respectively. Furthermore, the K_N of *L. japonica, U. pinnatifida,* and *U. pertusa* were 29, 17, and 26 μg N/l, and their K_P were 8.7, 6.2, and 8.0 μg P/l, respectively. The *Im* of *L. japonica, U. pinnatifida,* and *U. pertusa* were 720, 670, and 730 μ mol/mf2/s, respectively. The Q_{01} at P_N of *L. japonica, U. pinnatifida*, and *U. pertusa* were 1.071, 1.090, and 1.076, and their Q_{01} at P_P were 1.062, 1.081, and 1.084, respectively (Table.2).

O_2 production and consumption rates of seaweeds

The water temperature of the *P' cm* and *R' c* of *L. japonica, U. pinnatifida,* and *U. pertusa* was 23, 20, and 28 ℃, respectively. The *P' cm* of *L. japonica, U. pinnatifida*, and *U. pertusa* were 2.6, 2.7, and 2.8 mg O_2/mg chl.a/h, and their *R' c* were 0.29, 0.24, and 0.35 mg O_2/mg chl.a/h, respectively. The *P' cm/R' c* of *L. japonica, U. pinnatifida,* and *U. pertusa* were calculated at 8.9, 11.2, and 8.0, respectively (Table.3).

Discussion

Density of seaweeds cultured to N load of fish farm area

It was reported that N load rates per fish farm area of *S. quinqueradiata* in the *L. japonica, U. pinnatifida,* and *U. pertusa* cultivation periods were 290, 115, and 520 mg N/m_f^2/day, respectively (Kouchi Fisheries Experimental Station, 1989). The minimum densities of *L. japonica, U. pinnatifida,* and *U. pertusa* per fish farm area of S. quinqueradiata were analyzed by PmN, resulting in 2.9, 3.1, and 3.6 mg N/m_s^2/day, respectively. Thus, the minimum cultivation densities of *L. japonica, U. pinnatifida,* and U. pertusa per fish farm area of *S. quinqueradiata* cultured were 105, 27, and 7.6 kg/m_f^2, respectively (Table.4).

Weight and density of seaweeds cultured to O_2 consumption of fish culture

The oxygen consumption rate per an *S. quinqueradiata* cultured in the *L. japonica, U. pinnatifida,* and *U. pertusa* cultivation periods were 879, 695, and 1392 mg O_2/a fish/h, respectively (Kadowaki, 1990; 1994). The minimum cultivation weights of *L. japonica, U. pinnatifida*, and *U. pertusa* per *S. quinqueradiata* cultured were analyzed by *P' cm*, resulting in 0.75, 0.83, and 6.39 mg O_2/g wet/h, respectively. Thus, the minimum cultivation weights of *L. japonica, U. pinnatifida*, and *U. pertusa* per a *S. quinqueradiata* cultured were 1.70, 0.83, and 0.21 kg wet/a fish, respectively. Moreover, the minimum densities of *L. japonica, U. pinnatifida*, and *U. pertusa* per cage volume of *S. quinqueradiata* cultured were 5.6, 4.0, and 1.3 kg wet/m^3,

Table 1. Maximum growth and growth rate of blade length (BL) of *L. japonica* and *U. pinnatifida*, and thallus area (TA) of *U. pertusa*

Items	Unit	*L. japonica*	*U. pinnatifida*	*U. pertusa*
Layer	(m)	2.0	2.0	0.5
Blade length	(cm)	250	182	-
Thallus area	(cm^2)	-	-	640
Growth rate of BL	(cm/day)	3.0	4.2	-
Growth rate of TA	(cm^2/day)	-	-	7.6

Table 2. Maximum N and P uptake rates ($Pm_{N,P}$), the maximum irradiance to $Pm_{N,P}$ (Im), Michaelis-Menten constants (K), and the water temperature coefficients (Q_{01}) of *L. japonica, U. pinnatifida*, and *U. pertusa*

Items	Unit	*L. japonica*		*U. pinnatifida*		*U. pertusa*	
		N	P	N	P	N	P
WT	(℃)	16 - 23		12 - 20		18 - 28	
Pm	(mg/m_s^2/day)	2.9	0.43	3.1	0.54	3.6	0.19
Im	(μ mol/m_f^2/s)	720		670		730	
K	(μ g/*l*)	29	8.7	17	6.2	26	8.0
Q_{01}		1.071	1.062	1.090	1.081	1.076	1.084

Table 3. Maximim O_2 production rates ($P'cm$) and O_2 consumption rates ($R'c$) of *L. japonica, U. pinnatifida*, and *U. pertusa*

Items	Unit	*L. japonica*	*U. pinnatifida*	*U. pertusa*
WT	(℃)	23	20	28
P'cm	(mg O_2/mg chl.a/h)	2.6	2.7	2.8
R'c	(mg O_2/mg chl.a/h)	0.29	0.24	0.35
P'cm / R'c		8.9	11.2	8.0

Table 4. Comparison of minimum density of seaweeds cultured per fish farm area for nitrogen load of *S. quinqueradiata* in *L. japonica, U. pertusa,* and *U. pinnatifida*

Items	Formula	Unit	*L. japonica*	*U. pinnatifida*	*U. pertusa*
N load rate of *S. quinqueradiata* *1	A	(mg N/m_f^2/day)	290	11	520
Pm_N	B	(mg N/m_s^2/day)	2.9	3.1	3.6
Weight of seaweed	C	(g wet/indiv.)	116	192	-
Area of seaweed	D	(m_s^2/indiv.)	0.11	0.26	-
Area per weight of seaweed	E	(m_s^2/kg wet)	-	-	19
Minimum density of seaweed per fish farm area	A•C / (B•D)	(kg/m_f^2)	105	27	-
	A / (B•E)	(kg/m_f^2)	-	-	7.6

*1 Kouchi Fisheries Experimental Station (1989)

Table 5. Comparison of minimum amount of seaweeds cultured per a fish, and minimum density of seaweed cultured per fish cage volume for O_2 consumption of *S. quinqueradiata in L. japonica, U. pertusa,* and *U. pinnatifida*

Items	Formula	Unit	*L. japonica*	*U. pinnatifida*	*U. pertusa*
Water Temperature		(℃)	23	20	28
Body weight of *S. quinqueradiata* *1		(kg)	2.0	1.8	2.6
Density of *S. quinqueradiata* per cage volume *1	A	(fish/m^3)	4.8	4.8	6.3
O_2 consumption rate of *S. quinqueradiata* *2	B	(mg O_2/a fish/h)	879	695	1392
Maximum O_2 production rate of seaweed	C	(mg O_2/g wet/h)	0.75	0.83	6.39
Minimum amount of seaweed per a fish	B/C	(kg wet/a fish)	1.17	0.83	0.21
Minimum density of seaweed per fish cage volume	A•B/C	(kg wet/m^3)	5.6	4.0	1.8

*1 Kadowaki (1990); *2 Kadowaki (1994)

respectively (Table.5).

The *P' cm/R' c* of *L. japonica, U. pinnatifida*, and *U. pertusa* were 8.9, 11.2, and 8.0, respectively, proving that the O_2 production rate of seaweed is eight to eleven times more than the O_2 consumption rate. Therefore, seaweed cultivation is effective on the O_2 supply of fish farms.

The present study clarified the estimated water purification methodology by seaweed that N and P uptake rates, and the O_2 production rate were fixed by the environmental factors of the dissolved inorganic nutrients, irradiance, and the water temperature on coastal fish farms.

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Model management plan to optimize production of marine tropical systems

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Abstract NOAA, the University of Puerto Rico Sea Grant College Program, and other federal, state, and private partners are proposing to develop model management plans suitable for tropical marine ecosystems. In this paper we offer a new ecosystem-based management scenario using aquaculture to optimize value and function of tropical island ecosystems. Experience in Puerto Rico offers an excellent opportunity to combine several management plans while maintaining the flexibility to work with user groups to manage and optimize sustainable production from marine tropical systems. Puerto Rico has several tropical ecosystems available for study ranging from the high energy coastlines found on the north coast to low energy, mangrove shorelines on the southwest coast. Coral reefs are prevalent in the east, south, and west. All Puerto Rico coastal communities have seen a decline in fishery resources and habitats with subsequent decline in monetary value. A new approach for coastal resource management is needed.

The key element in coral reef management is that large scale commercial removal of reef resources has proven basically unachievable on island coral reef systems and larger coral reef systems. There are many species but not a lot of any one species. Commercial operators travel farther to find commercial levels of catch until the reef is exhausted and out of balance. Our premise is that the reef should be maintained with minimum impact to foster tourism and some subsistence fisheries to keep populations intact to maintain ecological balance of the reef and possibly provide broodstock for offshore aquaculture. Proper placement of offshore aquaculture in water over 30 m and 2-5 km offshore, away from coral reef structures has minimal environmental impact. With guidance from coral reef experts and aquaculturists, island communities can decide to combine marine protected areas, habitat protection, tourist scenic reefs, rigorous fisheries management and enforcement, and innovative marketing to optimize the value of coral reef systems. Technology exists to implement these management tools. Culebra Island, Puerto Rico, offers an excellent location to demonstrate this assumption.

Culebra has attracted international attention by petitioning the government to establish a "no-take" marine reserve. The subsequent increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, Culebra community leaders have the opportunity to optimize the value from their coral reef systems and to protect their marine resources. Recent advances in the development of offshore, submerged, marine aquaculture technology for island locations provides a new tool to optimize production of marine tropical systems. A panel of reef specialists, enforcement agents, aquaculturists, and environmentalists would advise the community and develop a management plan to optimize scenic reefs, promote rigorous fisheries management and enforcement, and propose innovative marketing strategies.

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Introduction

Management of tropical marine systems has had varying degrees of success. These systems have been impacted heavily, resulting in detrimental impacts in many areas. Many approaches are suggested: closed fisheries, seasonal closing, or maintenance of the status quo. In most coastal communities, environmentalists, non-government agencies, fishermen, and recreational users are concerned about their marine resources. Community-based decisions, guided by professional advice, provide a grass-roots approach to optimize production from marine systems. In this paper, we suggest offshore aquaculture as an additional tool for optimizing marine production.

During the Thirtieth Joint Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR) Aquaculture Panel Meeting in Sarasota, Florida, discussions entailed joint efforts to change the perception of aquaculture by developing environmentally sound aquaculture practices using broad-based ecosystem management that includes aquaculture and fisheries. Three priority areas should include on-shore recirculating systems, offshore aquaculture, and marine stock enhancement.

Increasingly complex aquaculture management strategies require a multifaceted approach involving many subject disciplines, human resources, and public and private institutions. This approach will include industry partners and community involvement, combined with strong research and collaboration related to coastal ecosystem modeling. The addition of aquaculture to these strategies could help alleviate the impact on the fisheries habitat while still providing healthy seafood products for the public. In this respect, US and Japanese aquaculture and fisheries in both the public and private sectors can work together to combine fisheries and aquaculture to improve marketing, exports, and value of fishery products in both countries.

One caveat of this paper is that we use the popular term "offshore" aquaculture to indicate open ocean conditions. Thus the term "offshore" in this paper does not have a legal context involving economic zones or legal boundaries. The popular term "mariculture" is a specialized word for "marine aquaculture"; we generally prefer to use the phrase "marine aquaculture".

Since 2001, Puerto Rico (PR) has maintained an offshore, submerged-cage aquaculture project (Fig. 1) similar to Hawaii's recent efforts. Based on cutting-edge technology developed in the US, a New York based company, Snapperfarm, Inc., has successfully grown two fish species in cages located 3 km southwest of Culebra, Puerto Rico. Snapperfarm worked for four years to write a business plan, obtain experimental permits from the PR Department of Natural and Environmental

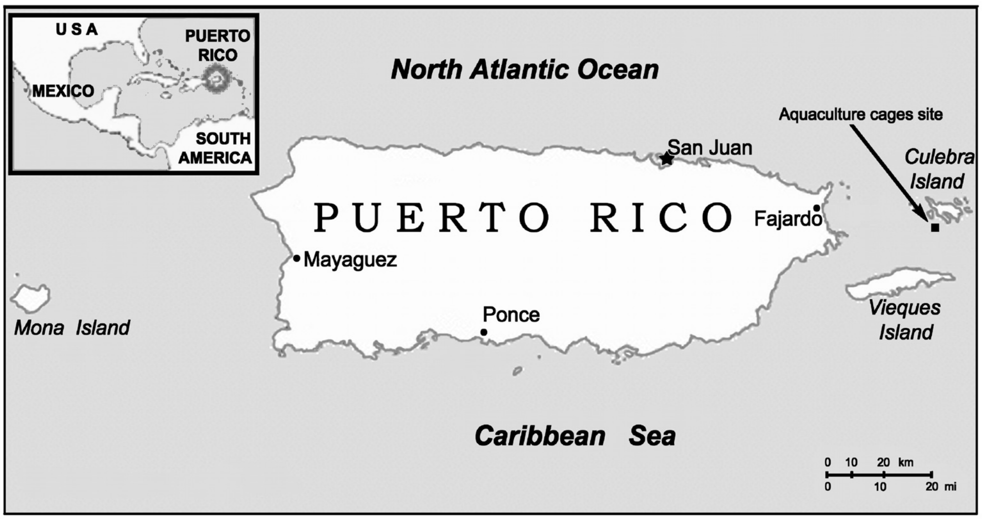

Fig. 1. Location of Snapperfarm offshore aquaculture cage site, Culebra, Puerto Rico.

Resources, assemble two submerged Ocean Spar Sea Station cages, and deploy them in 90-feet of water at the Culebra site. Snapperfarm's success has sparked the initiation of two other farms planning to install 16 more cages in Puerto Rico within two years. Growth of R. canadum (cobia) to 6 kg in one year has been the primary success factor driving this new industry with little environmental impact.

In addition to the marine aquaculture project, the island of Culebra has attracted international attention by petitioning the government to establish a "no-take" marine reserve (Causey 2002). The subsequent increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, we expect to persuade Culebra community leaders to continue to optimize the value from their coral reef systems by developing other marine protected areas (MPAs) to ensure habitat protection. For instance, the plan should include scenic reefs, rigorous fisheries management and enforcement, and innovative marketing.

The resulting increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, Culebra community leaders will have the opportunity to optimize the value of their coral reef systems to protect their marine resources. Simultaneously, marine aquaculture provides a new tool for managing island coastal resources to optimize production of marine tropical systems. A panel to advise the community would include reef specialists, enforcement agents, aquaculturists, economists, sociologists, and environmentalists to develop a management plan to optimize scenic reefs, promote rigorous fisheries management and enforcement, and propose innovative marketing strategies.

Deterioration of coral reefs

On a world-wide basis, coral reefs are at a 'fork in the road' (Wilkinson 2002). Either reefs will continue to decline due to increasing direct human stresses and indirect pressures of global climate change; or there could be major improvements in coral reef health in specific areas as a result of the conservation and management projects; or more likely coral reefs will travel down "both roads," with some reefs showing major improvements with increased coral cover, fish populations, and better

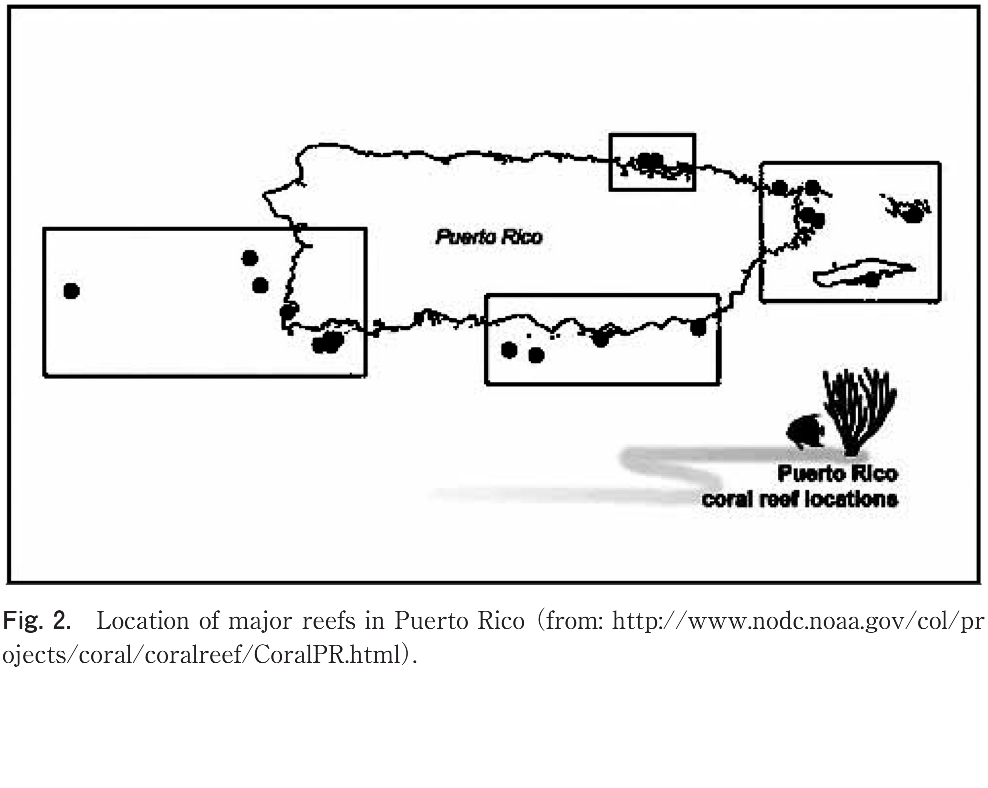

Fig. 2. Location of major reefs in Puerto Rico (from: http://www.nodc.noaa.gov/col/projects/coral/coralreef/CoralPR.html).

water quality, while many others will continue to lose corals and result in smaller fish populations and poor water quality.

Caribbean corals have been impacted. On Curacao, Netherlands Antilles, settlement of corals onto experimental plates has dropped from $22.8/m^2$ in 1981 to $3.0/m^2$ in 2001 (Wilkinson 2002). Many of the causes of coral reef decline have been identified and management techniques can be used to reduce pressures degrading coral reefs. It is imperative to apply this knowledge and demonstrate to coral reef user communities and their governments that coral reef conservation pays off in the long run.

In addition to the main island of Puerto Rico, there are 2 inhabited small islands off the east coast (Culebra and Vieques) and 3 uninhabited islands (Mona, Monito, Desecheo) off the west coast. Most coral reefs are located on the east, south, and west coasts (Fig. 2), with fringing reefs being the most common type. The western two-thirds of the north coast consists of mainly hard ground and reef rock with low to very low coral cover and some small, sparse, low coral colonies. The main islands of Puerto Rico, including Culebra and Vieques, are almost completely encircled by reefs, although coral reef abundance is highly variable, depending on local conditions (http://www.aims.gov.au/pages/ research/coral-bleaching).

Puerto Rico and related management plans

The Magnuson-Stevens (M-S) Act Fishery Conservation and Management Act set the standards for managing fisheries, so any plans must follow these guidelines. For instance, a fishery is defined as one or more stocks of fish which can be treated as a unit for purposes of conservation and management and which are identified on the basis of geographical, scientific, technical, recreational, and economic characteristics. Any plan must include the best scientific information available and be responsive to the needs of citizens. The term "conservation and management" refers to measures to rebuild, restore, or maintain any fishery resource and the marine environment to assure that the food or products taken is continuous, and that irreversible or long-term adverse effects on fishery resources and the marine environment are avoided. The terms 'over fishing' and 'overfished' mean a rate or level of fishing mortality jeopardizing the capacity of a fishery to produce the maximum sustainable yield on a continuing basis. The term 'fishing community' means a community which is substantially dependent on or substantially engaged in the harvest or processing of fishery resources to meet social and economic needs. The term 'optimum', with respect to the yield from a fishery, means the amount of fish which will provide the greatest overall benefit, taking into account the protection of marine ecosystems and prescribing for maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factor. In the case of an overfished fishery, the plan should provide for rebuilding to a level consistent with producing the maximum sustainable yield in such fishery.

These definitions allow considerable leeway to develop management plans to provide sustainable products with little environmental impact. However, many environmentalists want to close the resource to any human activity. While this may be suitable in some instances, most laws are designed to promote the best use of a resource.

The Department of Natural and Environmental Resources of PR (DNER) is responsible for the management of marine components (http://mpa.gov/mpa_programs/states/puerto_rico.html). The Natural and Marine Reserves are managed by the Natural Reserves and Commonwealth Forests Divisions of the Bureau of Reserves, Refuges, and Coastal Resources. Additional sites are administered and managed by the PR Conservation Trust. All of the sites included in the Marine Managed Areas Inventory have been designated by the Puerto Rico Planning Board, except Isla Desecheo Marine Reserve and Seven Seas Natural Reserve which was designated by the PR Legislature. Most sites have year-round protection, excluding three red hind (Epinephelus guttatus) spawning aggregation sites, which have a temporary fishing ban (December to February), designated by a joint effort between DNER and the Caribbean Fisheries Management Council. Many sites include critical habitat and essential fish habitat for endangered and threatened species including coral reefs, seagrass meadows, lagoons, mangroves, estuaries, wetlands, offshore keys, sandy beaches, and rocky shores. The sites protect a great diversity of endemic, endangered, and keystone species, both terrestrial and marine.

Fishermen are notoriously vociferous as a group. Because PR has a tradition of fishing, albeit at an artisanal level, they are generally supported by the government. Our suggestion is to include the major players in the decision-making process, including fishermen, environmentalists, non-government organizations, and representatives from the general community. Communities should have the choice of deciding the fate of fishery activities in their area. This grass-roots approach should make it easier for fishermen to accept new strategies. Efforts should be made to include the fishermen in proposed aquaculture activities. After all, they are familiar with marine operations and should continue to contribute their skills within their respective communities. A major problem is enforcement. By having the communities join in the decision-making process, we would hope the locals would provide self-enforcement, especially if MPAs would benefit the community as a whole.

We also suggest avoiding managing specific species; instead focus would be on maintaining the reef in optimum condition. This should greatly minimize expensive studies for each target species; instead effort could be re-directed toward optimizing the health of reefs.

Culebra Island as an example of community involvement

The Island of Culebra is 27 km east of Puerto Rico and is 11 by 5 km. The surrounding waters sustain an extensive and varied coral reef that is healthier than most others in Puerto Rico. The Culebra Fishermen's Association recognized that over fishing was a problem in their area with serious consequences for their artisanal fishing livelihood. Through their own initiative and with the assistance of a volunteer fisheries scientist, the association catalyzed the conservation effort by petitioning the Department of Natural and Environmental Resources of the Puerto Rico Government to designate a "no-take" zone on the west side of the island in 1999. The Biology Department of the University of Puerto Rico-Rio Piedras conducted scientific monitoring, both before and after the establishment of the reserve, and their results show that fish abundance increased dramatically and species numbers increased by 38%. Dramatic increases in the abundance (2,539%) and in the biomass (26,618%) of the yellowtail snapper (Ocyurus chrysurus) were noted, as well as significant increases in the abundance (414%) and biomass (868%) of the schoolmaster (Lutjanus apodus). Thus, the designation of the Luis Peña Channel No-Take Marine Reserve in Culebra, Puerto Rico is a clear demonstration of a grass-roots effort to manage local fisheries resources. Please refer to Hernández-Delgado and Sabat (2000) or Hernández *et al.* (2000) for additional details referring to the no-take marine reserve.

Dr. Sarah Keene Meltzoff, University of Miami, and Dr. Janet Bonilla, UPRM contributed to a socio-economic study of Culebra in relation to the new offshore aquaculture project by Snapperfarm. Most comments concerning the new cage culture industry were positive or neutral with a "let's wait and see" attitude. Several respondents indicated they would like to know more about the industry. Questions arose concerning the competition of the cages with the local subsistence fishing industry. Snapperfarm has repeatedly stated its goal to work closely with the Culebra Fishermen's Association and has voluntarily agreed to hire locals first to fill vacant positions; however, realities in education and work experience (professional diving, aquaculture experience) severely limit employment opportunities. This is an area that could be the focus for future projects, especially to train locals in offshore aquaculture techniques.

Community involvement and education

Any management process should include community involvement. All too often "top to bottom" plans impose new strategies and management policies for the natural resource without incorporating community ideas. Phillips (1998) used the term "social sustainability" which incorporates systematic community participation which will only be socially sustainable if it conforms to social norms or does not stretch them beyond a community's tolerance for change. If the community is not involved from the initiation of the project, imprecise or erroneous perceptions emerge. These perceptions become reality. Therefore the community must participate in the initial decision-making phase. Education becomes an essential component in these interactions and should be continued throughout each phase of the project.

Fong (1999) reported enhanced environmental responsibility and participatory self-governance by fishermen. The previous model utilized centralized governmental control and input that was distant in time, space, and purpose in relation to the local fisheries industry, which resulted in low productivity by the fisheries. Although centralized controls were set in place to cover a variety of environmental conditions, they were not appropriate for all local conditions. Such distant governmental control promoted neglect or outright damage to the environmental conditions, to the detriment the fishery in question. Taiwan tried a different approach to involve the communities by dividing their "counties" into individual units to develop policies unique to their area. This has the advantage of being site specific so plans can be adapted to varying hydrological and terrestrial habitats. When the local government worked with local fisheries associations and communities, productivity increased with increasing participation of fishermen and officials. Thus, Taiwanese fisheries cooperative practices were developed to involve the interaction of the community and the fishermen with technical input from the government (Fong, 1999).

Many legislators traditionally consider the ocean as a common property resource to be managed for all the people, assuring free and equal access (Corbin and Young 1997). Others have feared that leasing could lead to widespread subdivision of ocean space by large, financially well endowed companies, thus taking away the use and enjoyment of ocean resources by the general public. Legislators are now considering the "best use" of the oceanic environment; however, care should be continued to provide for sustainable development. Ecosystem based management schemes could be the basis for these plans.

Whatever the management strategy developed, education needs to be included in the plan. The public will be more apt to accept new strategies when they understand the consequences of the "status quo" situation that benefits no one and will learn to appreciate the accrued benefits by incorporating suitable management plans to optimize the productivity of their marine resource. In addition, they will be able to make valuable suggestions to adapt the plans to their respective community. By playing a role in the decision-making process, community participants will be much more disposed to accept management plans that benefit the environment and the community. It is important to include the major players in the discussions, including fishermen, environmentalists, non-government organizations, and representatives from the general community. The discussion group should be advised by experts.

Offshore aquaculture as an additional management tool

The key element in coral reef management is that managed removal of reef resources has shown to be basically unachievable on island coral reef systems and even larger coral reef systems. Wilkinson (2002) reported the following:

All regions of the world report that human factors are behind the declining health of coral reefs. The major stresses are increased sediments and pollution by nutrients and toxic compounds, and reef damage from exploitation of fishes, invertebrates, algae, rock and sand, and constructions. The most extreme example from the 2002 Reefs at Risk analysis is that 88% of all reefs in Southeast and East Asia are under moderate to very high human pressures.

For Southeast and East Asia, Wilkinson (2002) reported that "most reefs continue to decline under increasing human impacts, except where there has been strong community involvement in MPA design and management. Unstressed and protected reefs are recovering from losses in 1998, but there was further bleaching in Japan in 2001, with 50% mortality on some reefs. By far the most serious threats are destructive and over-fishing, followed by coastal development, increased sedimentation, and pollution. Monitoring and management capacity is relatively strong, but not sufficient for adequate reef assessment and conservation."

Caribbean activities have been boosted with some new funding, but many the problems remain (Wilkinson 2002). The corals in Florida, US Virgin Islands and Puerto Rico are either declining or have not recovered after decades of losses. No-take reserves in Florida have larger fish populations than in fished areas, and public support for management is increasing.

Healthy coral reefs have many species, but not many of a particular species. Commercial operators travel more to find commercial levels of catch until the reef is exhausted and out of balance. Our premise is that it is better to maintain the reef with minimum impact to be used as a source of enjoyment for tourists and some subsistence activities, but to keep populations intact to maintain the reef in balance and possibly provide broodstock for offshore aquaculture. Proper placement of offshore aquaculture in water over 30 m and 2-5 km offshore, away from coral reef structures has minimal environmental impact. With guidance from coral reef experts and aquaculturists, island communities can decide to combine protected areas, habitat protection, tourist scenic reefs, rigorous fisheries management and enforcement, and innovative marketing to optimize the value from coral reef systems. Technology exists to implements these management tools.

FAO (1997) identifies environmental deterioration and land availability as important constraints for marine aquaculture. Over 70% of the total world population lives in Asian coastal areas (Phillips 1998); about 60% of the world's population currently lives within 60 km of the sea (Phillips 1998). Puerto Rico, with 3.9 million inhabitants occupying 9100 km^2, has a central mountainous region, thus forcing the majority of the population to live near the coast. Puerto Rico's coastal pollution is typical of many industrialized regions (eutrophication, sediments, and other contaminants), but deterioration is also exacerbated by intense recreational and artisanal fishery activities. Reef decline is widespread in Puerto Rico and the fishery is heavily impacted. Each of these factors will continue to impact coastal aquaculture; even land based operations utilize coastal waters to culture species such as marine shrimp and tropical aquarium fish.

The term "sustainability" is controversial and has several related factors that should also be considered with its usage. The concept of sustainability should include not only the ongoing operation and its long-term impacts on the environment and society, but also the infrastructure, materials, and regenerative capacity of the natural system which generates these latter items (Phillips 1998). Thus "sustainability" entails prolonged socially acceptable, economically viable, and technologically appropriate production without degrading the environment. Simultaneously, additional resources supporting the industry (i.e., feeds, wild juveniles) should be renewable, or if not renewable (i.e., hatchery reared juveniles), these resources should be replaced with suitable substitutes on a timely basis.

Environmentalists are justifiably disturbed that offshore aquaculture depends on feeds containing a high percentage of fishmeal. However, only a portion of fishmeal and fishmeal derived oils are used in fish culture operations. The rest is used in feed for food animals such as poultry, cattle, or swine and a portion is incorporated into pet foods. Feed suppliers are willing to incorporate other ingredients into high quality, high protein feeds, but farmers report inferior growth. Perhaps environmental costs are too high to continue using fishmeal in animal feeds. An international ban on fishmeal use will be complicated, however, because incorporating bycatch from fisheries operations or offal from processing procedures (like tuna, catfish, etc.) is considered a legitimate use of an otherwise wasted resource. Nevertheless, a fishmeal ban should not discriminate among various aquaculture sectors or by country. This complicated topic should be subject to multi-lateral deliberation with input from scientists, governments, and the fisheries industry. In the meantime, the marine aquaculturists should purchase feeds which minimize the incorporation of fishmeal. Recent studies indicate excellent growth from feeds containing a minimum of fishmeal.

Offshore aquaculture has been hindered because of the energetic oceanic environment, lack of suitable equipment, fingerling fish, and unclear policies and regulations concerning this nascent industry. Reviews of monitoring strategies and methods revealed the need for standardized approaches flexible enough to cover the wide range of environments in which fish farms are located (Cochrane *et al.* 1994; Codling *et al.* 1995; and Alston *et al.* 2004). Future challenges to offshore aquaculture include clarification of policies and regulations, strengthening marketing and distribution channels, coping with rapid growth of biofouling organisms, improving harvesting techniques, and establishing a source of marine fish juveniles to achieve a viable, sustainable industry. A dynamic, flexible strategic plan is essential for incorporating the needs of the private industry, optimizing support from the government, and providing for adequate research support from Puerto Rico universities. Evaluation of the industry should utilize assessment methodologies, including socio-economic considerations and comparisons with domestic and foreign offshore industries.

Marine aquaculture operations may have positive or negative effects on the environment (Phillips 1998). The environment may have positive or negative effects on aquaculture, especially if external factors continue to degrade the environment. Eutrophication may provide nutrients beneficial for aquaculture production, especially for oysters, clams, and mussels. However, toxic pollutants can damage aquaculture investments (Phillips 1998). Aquaculture operations may affect each other, especially where the carrying capacity is exceeded by rapid expansion of many farms within a limited area. Each of the suppositions mentioned generally refer to land-based or inshore mariculture operations. Offshore aquaculture avoids many of these factors. Thus far, studies by the University of Puerto Rico and the University of Miami of the Snapperfarm submerged cage operation have indicated negligible negative environmental effects. As expected, the "footprint" of the effects was limited to directly beneath the cage and attributed to a combination of nutrient release (uneaten feed, fish feces) and shading by the cage itself.

Fisheries production for Puerto Rico and the US Virgin Islands (USVI) averaged 3,360 MT (FAO, 2004) for the years 1993-2002 (Fig. 3). In 1996, there were 1758 fishermen with a total of 1501 vessels. Using conservative estimates (survival of 85%, mean weight of 6 kg) of Snapperfarm's actual stocking and fish mean weight after 12 mo, each cage should produce about 61 MT/per year (4 fish stocked/m^3* 3,000 m^3/cage * 0.85 survival * 6 kg/fish * 0.001 to convert kg to MT = 61 MT). Rachycentron canadum are stocked at 4-6 fish/m^3 and harvested at 6-10 kg/fish in Taiwan (Su *et al.* 2000), so Snapperfarm's stocking rates are similar to those used in Taiwan. Even though all the fish were not harvested at 10 months, we are assuming a survival of 85% after 12 months. Using these conservative numbers, only 55 cages of fish would produce tonnage equaling the entire Puerto Rico and USVI fishery production (3360 MT divided by 61 MT = 55 cages). Taiwan reported that 1,500 cages were in operation in 1999 with volumes ranging from 216 to 1,884 m3. Thus if Puerto Rico and the USVI operated 55 cages, they could alleviate fishing pressure on reefs and still maintain present fishery production levels.

Alternatively, the Snapperfarm cages served as fish aggregation devices (FADs). Most subsistence fishermen in Puerto Rico focus their efforts in inshore areas, so are dependent on reef species. This causes a high pressure on coral reef species (Weiler and Suarez-Caabro 1980). Hence, FADs to attract pelagic fishes are integrated into management strategies to enhance local fisheries. FADs serve as additional substrate, shade, and refuge from predators (De Silva 1982); as an additional food source; and offer a break in the monotonous offshore environment. Friedlander (1986) compared small-scale fishing-gear techniques at six FADs deployed off northeast Puerto Rico and found differences in species diversity between FADs and control areas, indicating FADs may enhance recreational fishing catch rates. Beets (1989) found that FADs not only aggregate fishes but also have the potential to enhance the recruitment of benthic artificial reefs. Offshore cages offer protection and substrate similar to other FADs and also supplement the nutrient supply in the area through feeding the cages which could serve as direct or indirect sources of food for opportunistic feeders (Koslow *et al.* 1988;

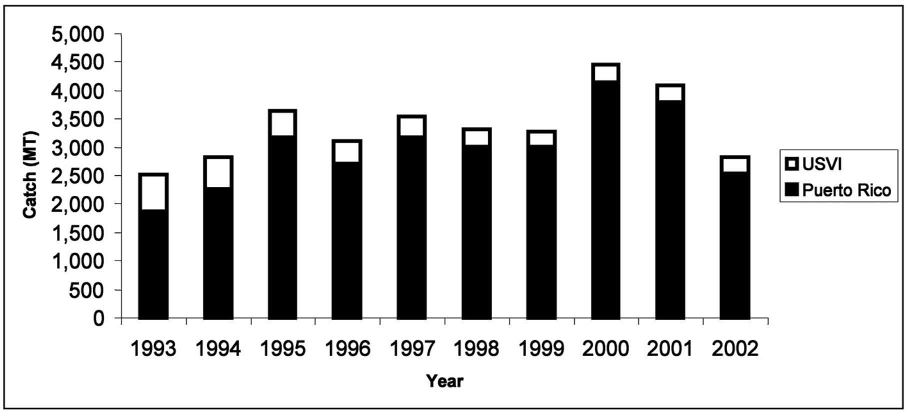

Fig. 3. Fishery landings for Puerto Rico and the US Virgin Islands, 1993-2002. Source FAO, 2004 (http://www.fao.org)

Humann 1994).

Because of the cage structures themselves and the constant food supply, we hypothesize that the offshore aquaculture industry could enhance the local fishery by facilitating new pelagic resources or serving as a source of recruitment to replenish impacted reefs. This could occur by two mechanisms. The fishermen could have access the aquaculture site to catch fish attracted to the cages. The cage site could serve as a "mini-reserve" where the cage site is restricted to fishermen. In the first case, fishermen could fish for pelagic species not normally accessible, therefore offering an additional income and economic options. However, fishermen would have to be careful to avoid damaging the cages. Pelagic fish species are not frequently captured by artisanal fishermen because of the difficulty and effort needed to find and capture these fishes. Fishing for pelagic species is more expensive.

However, fishery activities understandably makes cage aquaculturist nervous; so initially, Puerto Rican aquaculturists have decided to close their site to fishing. The second mechanism to allow the site to serve as a "mini-reserve" provides an opportunity for reef and pelagic species to use the cages as an artificial reef and spawning ground. Recruitment from the aquaculture site to area reefs could indirectly improve the fish catch on the reefs themselves. Thus, the first step was to determine the qualitative and quantitative composition, and the relative abundance of wild fish associated with the offshore cage site.

The Snapperfarm cages attracted 40 fish species from 23 families and 6 orders and mean fish abundance recorded near the cage site was approximately 40 times higher than at the control site (Bejarano *et al.* final preparation). Although the cage site was located in offshore conditions approximately 1 km from the nearest reef, 23 reef species, and 17 pelagic species were observed aggregating near the cages. Twelve reef species included juvenile individuals in most of the observations. Thirty-one of the species found near the cages are commercially important in Puerto Rico, representing 43% of the total numbers of individual recorded. Of the commercially important fish, 94% are used for human consumption (10 pelagic species and 8 reef species) and 6% are used by the aquarium industry. The majority of the fish used for human consumption were pelagic fish swimming in schools with numerous individuals. Some species exhibited a solitary behavior such as Sphyraena barracuda, Scomberomorus cavalla, Scomberomorus regalis, Ginglymostoma cirratum, Dasyatis americana, Aetobatis narinari, and Lutjanus jocu. Many were seen several times by the divers, usually moving away if closely approached.

Our data indicate submerged aquaculture cages are suitable for juvenile fish, acting as artificial habitats with additional substrate, refuge, and food. Artificial habitats in tropical waters attract reef fishes and contribute to artisanal fishing activities (Johannes 1997). With appropriate management strategies, fishermen could work with cage-culture operations, possibly kindling a proprietary and protective interest in fishing grounds. Fish collectors often become active stewards, guarding the resources against destructive uses and often creating conservation areas (Galvez 1991).

The rate of accumulation and coverage of biofouling organisms attached to the surface of the cage netting were assessed because they obstruct water flow through the cages, add additional weight to the cage, and increase the net drag. Even though biofouling was apparently not a problem in Hawaii's submerged cages (Helsley 2002), Snapperfarm reportedly cleaned their cages biweekly, thus, significantly increasing their operational costs. Because growth conditions apparently are optimum for biofouling growth, this provides an interdisciplinary opportunity to look for suitable organisms which could be grown quickly and harvested within a short time.

Although Puerto Rico historically has not cultured seaweed, the climate is suitable for tropical seaweed culture. By contrast, the Philippines produces 895 mt of aquatic plants (mostly marine algae) (http://www.fao.org/fi/statist/statist.asp), including Eucheuma alvarezii and E. denticulatum (Trono 1981). A separate species of Eucheuma isiforme is reported from Puerto Rico (Ballantine and Aponte 2002). Each has a tropical marine environment, so Puerto Rico should be suitable for seaweed culture. Ballantine and Aponte (1997) reported 473 benthic marine algae, some of which could be useful for culture.

Areas for collaborative efforts

Possible US and Japanese collaborative efforts related to optimizing production in the marine environment:

- "Culture" useful algae outside of cages instead of letting "wild" biofouling organisms dominate; in tropical conditions biofouling growth is rapid and results in economic loss for the aquaculturists due to frequent cleaning procedures.
- "Culture" filter-feeding pearl oysters on or near the cages to minimize wastes.
- Place urchins on cages to consume biofouling and explore markets for sale of urchin roe.
- Enhance BMPs (best management practices).
- Develop standardized monitoring techniques for cages.
- Automation of harvest system.
- Automation of feeding systems.
- Automation of cleaning biofouling from cages.
- Improve cage technology (shape, resistance to hurricanes/typhoons, maximize volume per dollar spent).
- Share information concerning disease and parasite infestations.
- Develop feeds with little environmental costs (i.e., without using fishmeal) that support rapid fish growth.
- Develop methodologies to measure genetic dilution from fish escapes.
- Compare carrying capacity per unit area (i.e., kg/km^2) of tropical versus temperate systems.
- Model nutrient flow (i.e., nitrogen into fish flesh, uptake by biofouling or sediment, dissolved nitrogen in water column).
- Compare discharge permit regulations.
- Compare social perception of cage culture operations.
- Study evidence of benign or beneficial interactions with the environment rather than solely concentrating on the devastation of accidental releases, eutrophication due to over feeding, or overproduction in a confined body of water (Helsley 2001).

Conclusions

Offshore aquaculture needs to confront problems inherent to the industry, especially those that seem "unavoidable" at the moment. These include the acknowledgment that unforeseen disasters could:

- Cause the escape of thousands of culture animals with little genetic diversity thereby possibly diluting the gene pool of native fish.
- Result in large-scale havoc by escapees on local reef ecology (predation, competition, etc.)
- Spread of parasites and diseases to wild populations. The inherent crowding of cultured fish provides ideal conditions for parasites and diseases.

The public has acknowledged and accepted that land agriculture perturbs the environment; the same will be true of offshore aquaculture.

However, by integrating aquaculture as an additional tool to manage marine tropical systems, reefs can be protected while the community can benefit from aquaculture fish yields. In the meantime, we need to continue to determine the environmental effects of marine aquaculture. Except for unforeseen natural disasters, the potential benefits of marine aquaculture seem to outweigh the negative aspects.

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New approach for the integrated aquaculture management from the view point of multi-functional role of fisheries and aquacultures

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Abstract: Supply of food, in particular of protein has long been widely accepted as major role of fisheries and aquaculture for human society. However, recent growing concern on the global environmental issue and sustainable development is now making clear that fisheries and aquaculture also play important roles on material cycling between land and sea, monitoring of fishing environment and living resources, purification of pollutant through biological activities and food chain, environmental watching by fisherman, environmental education, eco-tourism and etc. In this context, Science Council of Japan submitted a special report to the Minister of Agriculture, Forestry and Fisheries recently (Aug. 2004) on multiple roles and functions of fisheries and fishing communities, in which role on environmental conservation, role on formation of regional community, role on maintaining personal security, role on providing fields of education and many kinds of amenity were highlighted as well as the role of food supply. Responsible and sustainable aquaculture also can play important functional roles. As an example of possible new approach for the integrated aquaculture management from the view point of multi-functional role of aquaculture, present status and possible future direction of large scale oyster culture in Hiroshima Bay, Japan are discussed. For the future direction, integrated oyster culture management responsible for regional economy and community are proposed with particular reference to safe and clean oyster meat supply, benthic living resource enhancement by raft oyster culture system, recovery of discharged N and P from land, environmental and red tide monitoring system, many varieties of recreation, seascape, eco-tourism and environmental education for especially younger generation. This proposed management should be involved in the more holistic environmental and ecosystem management by wide variety of stakeholders as a part of integrated coastal management of Hiroshima Bay including land use management of Ohta River watershed which has strong influence on the biological productivity and diversity of Hiroshima Bay.

Key words: multi-functional role, integrated aquaculture management, oyster, Hiroshima Bay

Introduction

A major role of fisheries and aquaculture which has long been widely accepted and is still primarily important is supply of food, in particular of protein, for human society. However, new ideas on the concept of multi-functional roles of fisheries and aquaculture are now growing public concerns in the environmental conscious society under the global environmental crisis. In the symposium on "Role of Fisheries in Environmental Management and Remediation" held in 2001, Matsuda (2002) pointed out another six possible functional roles described below in addition to food supply, which are closely related to environmental conservation, purification of polluted environment and prevention of eutrophication: 1) Conservation of habitat environment, 2) Monitoring of environment and

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living resources, 3) Recovery of inflowing nutrients (nitrogen and phosphorus) through fish catch and harvesting, 4) Reduction of COD (chemical oxygen demand) value through biological activities, 5) Environmental watching by fisherman, and 6) Environmental education, eco-tourism.

In this context, fisheries and aquaculture which is to be discussed in the present paper indicate primarily responsible fisheries and aquaculture, and hence, do not include such destructive fisheries or aquaculture as had ever given strong negative impact on the fisheries environment and living resources.

Fundamental Law on Fisheries was enacted in Japan in 2001, in which the term "multiple functions of fisheries and fishing community" officially appeared and the necessity of future investigation on these functions was clearly stated.

In February, 2003, "International Symposium on Multiple Roles and Functions of Fisheries and Fisheries Communities" was held in Aomori, Japan, where Hiroyoshi (2003) made a key note lecture, in which he stated "There has not been awareness among people regarding multiple functions of fisheries communities. There is a need to renew our recognition in this respect from the view point of structural changes in fisheries as well as the earth's environment".

The Ministry of Agriculture, Forestry and Fisheries of Japan made an announcement on the new policy from 2004, main concept of which is more environmental conservation concerned agriculture, forestry and fisheries through healthy water circulation, healthy atmospheric circulation, healthy material circulation and conservation of healthy local communities.

In August, 2004 the Science Council of Japan submitted a special report to the Ministry of Agriculture, Forestry and Fisheries of Japan on the multiple roles and functions of fisheries and fishing communities with particular reference to role on food supply, environmental conservation, formation of regional community, people's security and providing fields of education and many kinds of amenity.

Thus, public awareness and interest on the multi-functional roles of fisheries is rapidly increasing during recent few years. In the present paper, under these circumstances, five selected multi-functional roles of fisheries and aquaculture below are highlighted and reviewed in order to clarify those functional roles with particular reference to environmental conservation, purification of polluted environment and prevention of eutrophication: 1) Material cycling between land and sea, 2) Monitoring of environment and living resources, 3) Purification of polluted environment through biological activities and process of food chain, 4) Environmental watching by fisherman, and 5) Environmental education.

Therefore, main objective of the present paper is not to show experimental data but to propose new concept and approach for the integrated aquaculture management from the view point of multi-functional role of fisheries and aquacultures.

Exemplified multi-functional roles of fisheries and aquaculture

1. Material cycling between land and sea

Landing of fish catch by capture fisheries is a valuable and rare process by which inflowing nutrients to the sea such as nitrogen and phosphorus are recycled to the land. Non-feeding aquaculture such as bivalve culture and algal culture also contributes to the same type of processes. Since anadromas fishes such as salmon play a same role on the material cycling between land and sea, conservation of normal behavior of anadromas fish can contribute to this function.

The magnitude of the recovery of inflowing nitrogen and phosphorus by fisheries is sometimes not so small and that in the Seto Inland Sea is estimated as 5 to 8% for nitrogen and 15 to 22% for phosphorus.

2. Monitoring of environment and living resources

Fishing boats encounter many kinds of oceanographic and meteorological evidence or phenomena and can collect huge amount of data which has high possibility to build up valuable data base. Fisheries statistics in particular of fish catch data in terms of weight according to species are valuable information of living resources particularly in Japan. Although fish catch data do not directly indicate fish resource data, no other similar biological data base are available covering such a long term and wide area of the sea as to many species. By the careful analysis of fish catch data, evaluation of living resource and estimation of the change in ecosystem structure is possible.

3. Purification of polluted environment through biological activities

During a process of food chain, filter feeders such as bivalves purify water through filtration of particulate matter and detritus feeders purify sediment through decomposition of organic matter. Not only detritus feeders but also aquatic animals generally decompose organic matter through heterotrophic nutrition resulting in the reduction of BOD, COD values of water and sediment. Another purification process regarding biological activities is removal of pollutant. When any kind of organic matter in the area is carried out by some migration or behavior of animals, this kind of removal of organic matter from the area in question is also evaluated as a kind of purification of the area in the broad sense. Filtering activities by bivalves estimated by some authors depends on conditions but generally very significant. With use of those effects of filtering activities of bivalves as well as the removal of N and P through catch of the bivalves, environmental restoration of tidal flats is made in some coastal area of Japan, for example, in Mikawa Bay, to enhance the production of clam shells as Manila clam.

4. Environmental watching by fisherman

Fisherman is a careful watch on marine environment, who can find out any kind of abnormal conditions such as red tide, oil spill or accident. Therefore, when the legal right of fishing of some area became null and void due to some reason, environmental conditions of the area often deteriorated historically because of the luck of watching and objection against deterioration. Original information on abnormal conditions, occurrence of red tide for example, often comes from fisherman. Therefore, networking of the information collected by fisherman potentially can play an important role on environmental conservation. Fisherman on the boat also sometimes rescues and saves people in crisis.

5. Environmental education

Fisheries and aquaculture provide us with valuable opportunity for environmental education and recreation. Excellent fishing ground and fisheries community are attractive site for eco-tourism. Not only that fish landing market is a part of informative eco-museum on living resources but also cooking fish at home can help the understandings of children for introductory anatomy and zoology. In Japan, access to natural seashore has been historically restricted by new land reclamation or port development, combined activities of recreation, seascape, eco-tourism and environmental education such as shellfish gathering is recommended for better understanding of marine environment and living resources, especially for younger generation.

New approach for possible integrated oyster culture in Hiroshima Bay

Among a number of multi-functional roles of fisheries and aquaculture which has already been exemplified in the previous section, oyster culture has many positive aspects of functional roles of aquaculture. Matsuda *et al.* (1999) already reported on the new perspectives for oyster culture as a biofilter and biohabitat. According to Songsangjinda *et al.* (1999, 2000), role of oyster culture in Hiroshima Bay on material cycling is valuable. However, production of oyster from Hiroshima Bay has been decreased due to multiple reasons. Main objective of the present proposal is to maximize any kind of positive effect of oyster culture and to minimize negative effect at the same time. As positive effects, in addition to supply of high quality oyster meat which is primarily important, purification of seawater by filtering activity of oyster, enhancement of material circulation through harvesting, providing variety of habitat for living organisms by culture gear, effect of oyster raft as floating algal bed, effects on recreation, amenity and education are pointed out. Oyster culture of Hiroshima Bay has valuable experience of monitoring and management of paralytic shellfish poisoning (PSP) in which monitoring of causative phytoplankton and toxicity of shellfish were made. While, as negative effects, deterioration of sediment quality by deposition of feces and pseudofeces due to excessive culture, inhibition to tidal movement by more than 10,000 floating culture rafts, occurrence of PSP, effect of waste from oyster culture industries can be listed up. Not a small amount of waste from culture system such as foam polystyrene from float and PVC pipe from oyster hanging wire system have been ever reported in and around culture ground.

Under these circumstances, future integrated oyster culture management in Hiroshima Bay should be responsible for regional environment, economy and community. Hirata and Akashige (2004) analyzed the present situation and problem of oyster culture in Hiroshima Bay and pointed out, as one of the problems, dense cultivation which prolonged the culture period due to low phytoplankton level. They also showed with use of model that the reduction in oyster biomass in the culture ground is needed to solve the problem and that shortening of the culture period was the most effective method without reducing harvest magnitude.

In addition to safe and clean oyster meat supply, benthic resource enhancement with particular reference to sea cucumber resource enhancement under oyster raft is recommended partly because oyster culture system is an excellent collector of sea cucumber larva. In addition to the recovery of discharged N and P from land, improvement of environmental and red tide monitoring system are also proposed. This proposed integrated oyster culture management should be involved in the more holistic environmental and ecosystem management by wide variety of stakeholders as a part of integrated coastal management of Hiroshima Bay including watershed and land use management of Ohta River watershed which has strong influence on the biological productivity and diversity of the ecosystem in Hiroshima Bay. Interdisciplinary investigation on the restoration of deteriorated Hiroshima Bay environment also started in April, 2004 by the prefecture government.

Closing remarks

Although primary objectives of the integrated aquaculture will be to supply safe and high quality food, future direction for integrated aquaculture management should be sustainable in its manner, responsible for human society and playing as much multi-functional roles of aquaculture. Integrated aquaculture management to enhance regional economy and employment should also contribute to build up healthy material circulation and healthy ecosystem. In order to maximize multi-functional roles of fisheries and aquaculture, collaboration is recommended with holistic regional environmental management as a part of integrated coastal zone management which includes watershed area management. It is also proposed for integrated aquaculture management from the view point of multi-functional role of aquaculture to minimize waste material, to reuse waste material, to reduce energy consumption, to reduce new resource consumption, to restore deteriorated environment and to collaborate with variety of stakeholders.

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