Advantages of Environmentally Sound Poly-eco-aquaculture in Fish Farms

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Abstract

Environmentally sound poly-eco-aquaculture enables the preservation of aquatic environments to be compatible with that of sustainable aquaculture. With this method, not only healthy fish can be cultured in purified water, but also the productivity will increase by recycling seaweed to feed fish. The maximum nitrogen uptake rate of each seaweed per square meter of seaweed area was 2.9 mg N/m_s^2/day for *Laminaria japonica*, 3.1 mg N/m_s^2/day for *Undaria pinnatifida* and 3.6 mg N/m_s^2/day for *Ulva pertusa*. The maximum phosphate uptake rate was 0.43 mg P/m^2/day, 0.54 mg P/m^2/day, and 0.19 mg P/m^2/day. The calculated values of nitrogen and phosphate uptake rates, obtained by integrating the nutrient concentrations, light intensity, and water temperatures, corresponded well with each observed value. The minimum seaweed cultural density necessary per unit area of *Seriola quinqueradiata* farm was calculated using the values of the maximum nitrogen uptake rate. The maximal production rates were 0.75 mg O_2/g wet/h for *L. japonica*, 0.83 mg O_2/g wet/h for *Un. pinnatifida*, and 6.39 mg O_2/g wet/h for *Ul. pertusa*. The minimal weight of cultured seaweeds necessary to accommodate the oxygen consumption of an individual *S. quinqueradiata* was calculated as 1.17 kg wet/a fish, 0.83 kg wet/a fish, and 0.21 kg wet/a fish.

Key words: Poly-eco-aquaculture; Seaweed; N,P uptake; O_2 production; Fish farm

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The industry of marine aquaculture in the 21st is expected to be practiced in harmony with the environment. It is our responsibility to hand down a blue and abundant sea for our future generations to inherit. Environmentally sound poly-eco-aquaculture is a technical innovation of aquaculture used to purify water and promote a balanced ecosystem by breeding seaweed and shellfish around coastal fish farms. The seaweed is used to feed for fish and shellfish. 'Eco' in the word "eco- aquaculture" means a harmony of ecology for nature and economy for humanity.

In order to establish coastal fish farms which enable sustainable aquaculture, there is a recent requirement for concrete measures to be taken to improve water quality in the farms. Biological water purification is necessary for preventing eutrophication of water and for reducing oxygen deficiency in water (Kadowaki 2001, 2004). Seaweed cultivation is currently attracting much attention as a plausible measure in this plight.

When seaweed is cultivated in the eutrophied water of coastal fish farms, it uptakes dissolved inorganic nitrogen and dissolved inorganic phosphate while supplying dissolved oxygen, which is essential for the farms.

Aiming to improve the water quality of coastal yellowtail farms in warm water zone over a year long period, different seaweed species were cultivated in the farm during each season. 'Wakame' *Undaria pinnatifida* was grown during the winter months, 'Konbu' *Laminaria japonica* in the spring, and sea lettuce *Ulva pertusa* in the summer and autumn. Following this, the relationship between nitrogen and phosphate uptake rates, oxygen production rate by the different seaweeds, and the nutrient concentration, light intensity, and temperature of the water in the farm was estimated (Kitadai and Kadowaki 2003, 2004a, 2004b, Kitadai 2005). Next, the improvement in nitrogen uptake in relation to nitrogen load by yellowtail aquaculture, as well as the cultivation scale of seaweeds necessary for oxygen production in relation to oxygen consumption per individual yellowtail and per cubic meter of the net cage, was estimated.

This study exemplifies the extent to which water quality of feeding fish farms was improved by cultivating seaweed, proposing specific measures.

1. Heavy Environmental Load by Mono-aquaculture

The mainstream in predominant fish cultivation has been that of mono-aquaculture breeding only one kind of fish. With this method, oxygen consumption by the cultured fish increases, and the load of carbon dioxide becomes heavier. In addition, nutrients, such as nitrogen, and phosphates from feces or remaining fish feed, dissolve in the sea water, making the water eutrophied. This causes red tide, fish pathologies, and oxygen deficiency in sea water, resulting in the mass mortality of fish, auto-pollution, and so on.

This was a significant problem in the Southwestern part of the Yatsushiro Sea in 2002, when the nitrogen load by fish aquaculture reached seven hundred to twenty-six hundred times that of the nitrogen uptake by seaweed breeding (Kadowaki and Kitadai 2005).

2. Environmentally Sound Poly-eco-aquaculture

In order to create a truly rich production by cultured fish, we would like to propose that in the part where the balance of ecosystem has been broken, the balance of ecosystem is restored by the introduction of poly-eco-aquaculture which directly utilizes solar energy as shown in **Fig.1**. The primary principle of poly-eco-aquaculture is breeding seaweeds, such as *Un. pinnatifida*, *L. japonica*, and *Ul. pertusa* throughout the year for the artificial formation of sea forest around cultured fish cages. The seaweed will uptake nutrients, such as nitroge, and phosphate from fish feces and remaining feed. The seaweed also inhibits pathogenic bacteria (Nagahama and Hirata 1990) and red tide (Hirata et al 1986). Grown seaweeds will be fed to abalone (*Haliotis discus hannai, Haliotis discus discus, Haliotis gigantea*), sea urchin (*Stichopus japonica*, *Holothuria pervicax*), yellowtail *Seriola quinqueradita* and red sea bream *Pagrus major*. Sea cucumber *Stichopus japonica* is grown in symbiosis with abalone in aquaculture net cages. Feces of abalone are fed to sea cucumber. Scallop *Chlamys nobilis* can be cultured because they eat organic suspended substances, such as remaining feed and the fish feces. Environmentally sound poly-eco-aquaculture enables the preservation of aquatic environments to be compatible with that of sustainable aquaculture. With this method, not only healthy fish can be cultured in purified water, but also the productivity will increase by recycling seaweed to feed fish.

When cultured abalone and sea cucumber are dried, they can be stored for long periods and can be shipped long distance at room temperature. It was also found that half pearls could be grown in cultured, giant abalone *Haliotis gigantea* in five months after a nucleus was inserted into it. The shells can also be used for mother of pearl work. With poly-eco-aquaculture, there is a higher additional value, as well as expectation of increasing job opportunities.

The capability at which seaweeds can uptake nitrogen has been researched, and it was found that the purification of aquatic environments to allow the amount of cultured fish became feasible when the area of seaweed breeding was more than the area of fish aquaculture. Based on the research results, Azuma-cho Fisheries Co-operative Association decided in 2000 to employ seaweed breeding near the marine aquaculture farm in an effort to increase the proportion of the area of seaweed to the area of fish aquaculture, aiming at safe, sustainable aquaculture. The fishermen themselves are practicing poly-eco-aquaculture.

3. The Cultural Density of Seaweed Necessary for Water Purification in Fish Farm

This study was conducted in fish farms producing *S. quinqueradiata*, *P. major* and puffer fish *Takifugu rubripes* in Gosyoura-cho, Kumamoto Prefecture, located in the southeastern part of the Yatsushiro Sea as shown in **Fig.2**. During the research, the water temperature and oxygen concentration 3 m below the sea level in fish farms A~E were measured every three hours. The dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate(DIP) concentrations 2 m below the sea level in fish farms were analyzed once a week (Strickland and Parsons 1972). The light intensity at 1.3 m and 2.0 m below the sea level was measured automatically every hour using a photo sensor, 190SA of LI-COR Biosciences.

L. japonica was cultivated between December of 2000 and July of 2001, *Ul. pertusa* was cultivated during August of 2002 and November of 2002, and *Un. pinnatifida* was cultivated from November of 2002 to May of 2003, respectively. Fish farms in Gosyoura-cho, Yatsushiro, obtain seed yarns of *Un. pinnatifida* and *L. japonica* from Yoshida Fisheries Ltd. in Shimabara-city and Aomori Fisheries Farming Center in late November (below 21℃) and late December (below 20℃), respectively. The hanging layer of *L. japonica* and *Un. pinnatifida* was between 1m and 4 m below the sea surface, while that of *Ul. pertusa* was between 0.5 m from the sea level.

The blade length of *L. japonica* and *Un. pinnatifida*, as well as the blade area of *Ul. pertusa*, were identified and measured twice a month. Also, the area, wet weight, dry weight, nitrogen content, and phosphate content of the different seaweeds were measured every month to obtain observed values of nitrogen and phosphate uptake rates. The nitrogen and phosphate uptake rates ($P_{N,P}$, mg N,P/m^2/day) in relation to the seaweed area was calculated using the following equation:

$$P_{N,P} = (C_{N,P\,t} - C_{N,P\,0}) \cdot \alpha / t$$

$C_{N,P\,0}$ represents the nitrogen and phosphate content (mg N,P/g dry) on the initial day of the experiment, while $C_{N,P\,t}$ represents the nitrogen and phosphate content (mg N,P/g dry) t days after the experiment started. α represents the dry weight of the seaweed per square meter of seaweed area (g dry/m^2), while t represents the number of cultivation days.

The oxygen production rate and oxygen consumption rate were measured over four hours from 10:00 to 14:00 during fine weather conditions using light and dark oxygen bottles, whose value per unit of chlorophyll-a was shown. The hanging level of oxygen bottles for *L. japonica* and *Un. pinnatifida* was 2 m below the sea surface, while that for *Ul. pertusa* was 0.5 m from the sea surface. Oxygen concentration was titrated using Winkler's method. The relationship between the nitrogen and phosphate uptake rates ($P_{N,P}$, mg N,P/m^2/day), as well as the oxygen production rate ($P'c_{N,P}$, mg O_2/mg chl.a/h) of the seaweed area and DIN, DIP concentrations in the fish farm, was analyzed using the Michaelis-Menten's formula (Dudale 1967). The $Pm_{N,P}$, $P'cm$ and K were calculated by the following formula:

$$P_{N,P} = Pm_{N,P} \cdot S_{N,P} / (K_{N,P} + S_{N,P})$$

Where, $Pm_{N,P}$ represents the maximum nitrogen and phosphate uptake rates of seaweed area (mg N,P/m_s^2/day), $S_{N,P}$ represents DIN and DIP concentrations (μg N,P/l). $K_{N,P}$ represents the minimum DIN and DIP concentrations for growth of seaweed as Michaelis-Menten's constants (μg N,P/l).

$$P'c_{N,P} = P'cm_{N,P} \cdot S_{N,P} / (K_{N,P} + S_{N,P})$$

Where, $P'cm_{N,P}$ represents the maximum oxygen production rates of seaweed chlorophyll-a (mg O_2/mg chl.a/h).

The minimum nitrogen and phosphate concentrations necessary to obtain the maximum nitrogen and phosphate uptake rates and the maximum oxygen production rate, were calculated. The relationship between the nitrogen and phosphate uptake rates of the seaweeds, and light intensity was analyzed using the Steel formula (Steel 1962) in order to obtain the optimum light intensity for the maximum nitrogen and phosphate uptake rates. The saturation irradiance Im (μ mol/m_f^2/s) to $Pm_{N,P}$ was calculated by the following formula:

$$P_{N,P} = Pm_{N,P} \cdot (I / Im) \cdot \exp(1 - I / Im)$$

Where, I represents the downward irradiance per a fish cage area (μ mol/m_f^2/s), Im represents the optimum light intensity to $Pm_{N,P}$. (μ mol/m_f^2/s).

The relationship between the nitrogen and phosphate uptake rates of the seaweeds, and water temperature, was analyzed by the Allometory formula (Kadowaki and Tanaka 1994) in order to obtain water temperature coefficients, $Q_{01\,\mathrm{N,P}}$. The $Q_{01\mathrm{N,P}}$ was calculated by the following formula:

$$P_{\theta\,\mathrm{N,P}} = P_{T\,\mathrm{N,P}} \cdot Q_{01\mathrm{N,P}}{}^{(\theta - T)}$$

Where, $P_{\theta\,\mathrm{N,P}}$ represents the $P_{\mathrm{N,P}}$ at θ℃ (mg N,P/m_s^2/day), $P_{T\,\mathrm{N,P}}$ is the $P_{\mathrm{N,P}}$ at T℃ (mg N,P/m_s^2/day), $Q_{01\mathrm{N,P}}$ represents water temperature coefficients, θ represents water temperature(℃), and T represents water temperature 20℃ for *L. japonica*, 16℃ for *Un. Pinnatifida* and 25℃ for *Ul. Pertusa*.

In addition, seaweed cultural density (kg wet/m_f^2) in relation to the area of a fish farm was calculated, which is necessary for the uptake of nitrogen load in fish aquaculture. Furthermore, seaweed cultural weight necessary for the oxygen consumption of individual *S. quinqueradiata* (g wet/a fish), and the seaweed cultural density necessary for oxygen consumption per cubic meter of the net cage (kg wet/m^3), were calculated.

1) Environment of the seaweed cultivation

The water temperature was between 12℃ and 28℃, and the oxygen concentration was in the range of 5.7 mg/ℓ and 10.7 mg/ℓ in fish farms during the seaweed cultivation period. The nitrogen concentration hovered between 31 μg N/ℓ and 150 μg N/ℓ, while phosphate concentration was between 7.0 μg P/ℓ and 27 μg P/ℓ. The ratio of nitrogen to phosphate was in the range of 3.1 and 8.4. The mean for downward irradiance of the layer 2 m below the sea surface (±standard deviation) was 650±74 μ mol/m^2/s.

2) Growth of seaweeds

The blade length of *L. japonica* and *Un. pinnatifida* grew up to 250 cm, and 182 cm respectively in the layer 2 m below the sea surface. The maximum daily growth rate of *L. japonica* and *Un. pinnatifida* was 3.0 cm/day, and 4.2 cm/day, respectively. The blade area of *Ul. pertusa* grew up to 640 cm^2 in the layer 0.5 m below the sea surface, and the maximum growth rate was 7.6 cm^2/day (**Table 1**).

3) Nitrogen and phosphate uptake rates of seaweed species

The maximum nitrogen uptake rate of each seaweed per square meter of seaweed area was 2.9 mg N/m_s^2/day for *L. japonica*, 3.1 mg N/m_s^2/day for *Un. pinnatifida*, and 3.6 mg N/m_s^2/day for *Ul. pertusa*, respectively. The nitrogen uptake rate of *Ul. pertusa* was the highest of all. The maximum phosphate uptake rate was 0.43 mg P/m^2/day, 0.54 mg P/m^2/day, and 0.19 mg P/m^2/day, respectively. In addition, the minimum nitrogen concentration necessary for the growth of *L. japonica*, *Un. pinnatifida*, and *Ul. pertusa* was 29 μ g/ℓ , 17 μ g/ℓ , and 26 μ g/ℓ , while the minimum phosphate concentration necessary for growth was 8.7 μ g/ℓ , 6.2 μ g/ℓ , and 8.0 μ g/ℓ respectively.

The optimum light intensity for nutrient uptake of *L. japonica*, *Un. pinnatifida*, and *Ul. pertusa* was calculated as 720 μ mol/m^2/s, 670 μ mol/m^2/s, 730 μ mol/m^2/s, respectively. Additionally, the water temperature coefficient, Q_{01}, in relation to the nitrogen uptake rate of each seaweed was 1.071, 1.090, and 1.076, respectively, while the Q_{01} in relation to the phosphate uptake rate was 1.062, 1.081, and 1.084, respectively (**Table 2**). The calculated values of nitrogen and phosphate uptake rates, obtained by integrating the nutrient concentrations, light intensity, and water temperatures, corresponded well with each observed value.

4) Production and consumption of oxygen by the seaweeds

Oxygen production rate and oxygen consumption rate of *L. japonica*, *Un. pinnatifida*, and *Ul. pertusa* were maximized when water temperature was 23℃, 20℃, and 28℃, respectively. The maximum oxygen production rate of each seaweeds was 2.6, 2.7, and 2.8 (mg O_2/mg chl.a/h), while that for the oxygen consumption rate was 0.29, 0.24, and 0.35 (mg O_2/mg chl.a/h), respectively.

With these values, the maximum oxygen production rate of the seaweed in reference to the oxygen consumption rate of individual fish was calculated as 8.9 for *L. japonica*, 11.2 for *Un. pinnatifida*, and 8.0 for *Ul. pertusa* (**Table 3**). This means that the oxygen production rate of the seaweed during the daytime under fine weather conditions is eight to eleven times as high as the oxygen consumption rate, indicating that seaweed cultivation would be effective for supplying oxygen to water in fish farms.

5) Seaweed cultural density in relation to nitrogen load in fish farm area

It has been reported that the nitrogen load rate per square meter of area of a yellowtail *S. quinqueradiata* farm during the seaweed cultivation period is 290 mg N/m^2/day for *L. japonica*, 115 mg N/m^2/day for *Un. pinnatifida*, and 520 mg N/m^2/day for *Ul. pertusa* (Kouchi Fisheries Experimental Station 1989). The minimum seaweed cultural density necessary per unit area of *S. quinqueradiata* farm was calculated using the values of the maximum nitrogen uptake rate obtained above 3). With the maximum nitrogen uptake rates of the seaweeds mentioned above, the minimum seaweed cultural density necessary for the area of this particular *S. quinqueradiata* farm was obtained. The cultural density of *L. japonica* was 105 kg wet/m^2, 2 kg wet/m^2 for *Un. pinnatifida* and 7.6 kg wet/m^2 for *Ul. pertusa* (**Table 4**).

It is considered that the effective cultural density of *Ul. pertusa* in a fish farm is 3.0 kg wet/m^2 (Maesako et al 1985). For this reason, the nitrogen uptake rate of *Ul. pertusa* in relation to nitrogen load in a fish farm is calculated up to approximately 40% (3.0 / 7.6) when the area of cultured seaweed is the same as the area of the farm. In other words, the culture area of *Ul. pertusa* necessary to purify the nitrogen load in an inner bay fish farm is 2.5 times (7.6 / 3.0) as large as the fish farm.

6) Seaweed cultural density to oxygen consumption by cultured fish

The oxygen consumption rate of an individual *S. quinqueradiata* while *L. japonica*, *Un. pinnatifida*, and *Ul. pertusa* were cultured was calculated as 879 mg O_2/a fish/h, 695 mg O_2/a fish/h, and 1392 mg O_2/a fish/h, respectively (Kadowaki 1990, 1994). The required mass of the seaweed necessary to accommodate oxygen consumption by an individual *S. quinqueradiata* was calculated using the seaweeds' maximal oxygen production rate per unit weight of each seaweed species. The production rates were 0.75 mg O_2/g wet/h for *L. japonica*, 0.83 mg O_2/g wet/h for *Un. pinnatifida*, and 6.39 mg O_2/g wet/h for *Ul. pertusa*.

In addition, the minimal weight of cultured seaweeds necessary to accommodate the oxygen consumption of an individual *S. quinqueradiata* was calculated as 1.17 kg wet/a fish, 0.83 kg wet/a fish, and 0.21 kg wet/a fish, respectively. The minimum seaweed cultural density necessary to accommodate the oxygen consumption per cubic meter of the net cage was calculated as 5.6 kg wet/m^3 for *L. japonica*, 4.0 kg wet/m^3 for *Un. pinnatifida*, and 1.3 kg wet/m^3 for *Ul. pertusa* (**Table 5**).

Conclusion

From the results, it was obvious that all of the seaweed species had the capacity to take in nitrogen and phosphate loads and that they fulfilled the role as oxygen producers. However, it may be difficult for seaweed to completely take in nitrogen and phosphate loads alone. Even with *Ul. pertusa* which uptakes nitrogen and phosphate loads most effectively, it would take an area of *Ul. pertusa* two and a half times of area of a fish farm in order to take in the loads completely. Still, it is considered important to cultivate effective seaweed for the eutrophication of each fish farm and improve the water quality.

It was also shown that seaweed worked effectively in supplying oxygen. This indicates that it is both possible to reduce environmental load and supply oxygen necessary for feeding fish, in addition to managing the water environment, using seaweed.

Kadowaki (2006) have proposed a specific model on how to cultivate seaweeds as shown in **Fig.3**. It assumes that *L. japonica* and *Un. pinnatifida* are cultivated around cultured fish cages. The cultivation area is 4 m below the sea surface in consideration of the growth of seaweed and water exchange. Stem ropes, in which 10 cm length of seeding yarns are inserted by 10 cm spacing of seeding insertion, are hung down at 1 m intervals around the cage (Ohyama et al 2005). It is expected that 3.2 mt of *L. japonica* can be grown, and about 30% of the nitrogen load of feeding fish will be reduced with the grown seaweed.

The time to fully implement poly-eco-aquaculture is now ! In order to reproduce marine aquaculture farms, concrete measures need to be taken to promote year-round seaweed breeding inside and outside of fish farms, artificial formation of seaweed beds, reuse and circulation of output biomass of seaweed. Environmentally sound poly-eco-aquaculture answers the needs of both environment and industry, because it will enable environmental conservation through water purification, compatible with sustainable aquaculture that would culture healthy fish. When the sea is supported by the various groups of living things, the productivity of fish farms will be developed, and a rich sea having sustainable productivity might be realized. It is our hope that those in the aquaculture industry will try this eco-friendly approach to promote sustainable aquaculture.

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