Water Quality Control for Intensive Shrimp Culture Ponds in Developing Countries Using Ammonia-Nitrogen Uptake by Seaweed

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Keywords: Ammonia-Nitrogen Control, Ammonia-Nitrogen Uptake, Mariculture Pond Design, Shrimp Culture Ponds, Sterile Ulva sp.

We studied the practical use of seaweed to remove inorganic nitrogen, especially ammonia-nitrogen, from the intensive shrimp culture ponds in developing countries. At first, we considered and experimentally evaluated the performance of ammonia-nitrogen uptake by seaweed in terms of parameters essential to the designing of intensive mariculture ponds. Based on the mechanism of ammonia-nitrogen uptake by seaweed, it was predicted that the ammonia-nitrogen concentration in the shrimp culture pond could be controlled by keeping it lower than a certain limit of value using a sufficient amount of seaweed with a condition that the rate of ammonia-nitrogen generation was constant. Experimental ammonia-nitrogen uptake runs confirmed this prediction and gave the parameters essential to design the culture pond with seaweed. Secondly, the control of the pond water quality for the practical shrimp culture batch was simulated by simple calculation based on the material balance of ammonia-nitrogen with parameters obtained from the experiments. The concentration of ammonia-nitrogen could be favorably controlled using seaweed in the practical batch and this method found to be feasible. Consequently, the water quality control using ammonia-nitrogen uptake by seaweed was proposed as a simple and convenient method appropriate for the intensive shrimp culture pond in developing countries.

Introduction

Shrimp farms all over the world are facing serious problems of disease outbreaks. Especially white spot syndrome virus (WSSV) has heavily damaged world shrimp industry since the 1990s (Takahashi et al., 1994; Chou et al., 1995; Wang et al., 1995; Wongteerasupaya et al., 1996). Because WSSV infects almost all kinds of crustaceans including crustacean planktons, the only way to prevent its infection in shrimp farms is keeping shrimps away from external water containing infected crustaceans. Shrimp farms in developing countries are now shifting to closed systems in which water exchange rates are minimized (Wang, 1990). On the other hand, in these closed systems, a rapid accumulation of inorganic nitrogen, especially ammonia, occurs and the water becomes strongly toxic to shrimps (Chen et al., 1990), and reduces their growth rates even at low concentrations (Chen and Tu, 1991). Therefore, control of ammonia-N contents in culture ponds is one of the critical keys in intensive mariculture where the culture density is expected to increase from this time on. Nitrate-nitrogen is also better to be removed in order to keep the pond from eutrophication (Sato et al., 2006b), even though nitrate-nitrogen is said to be much less toxic than ammonia-nitrogen.

Biofiltration by seaweed is an attractive system in terms of its abilities not only to remove inorganic nitrogen effectively from the culture medium (Krom, 1986), but also to control the contents of oxygen, pH, and CO₂ in the medium in a favorable state (Hirata et al., 1994; Rai et al., 2000). There are several successful reports about a biofilter of Ulva lactuca to control nitrogen and phosphorus contents in intensive mariculture ponds of Sparus aurata in arid regions (Cohen and Neori, 1991; Neori et al., 1991; Krom et al., 1995).

Authors showed that sterile Ulva sp. was able to take in ammonia-nitrogen effectively in seawater under tropical conditions (Sato et al., 2006a). However, there is no engineering approach or methodology for the design of intensive shrimp pond controlled by seaweed, which has been conducted based only on empirical background so far.

In this study, we studied the practical use of seaweed to remove ammonia-nitrogen from the intensive shrimp culture ponds in developing countries. In the first, we considered and experimentally evaluated the performance of ammonia-nitrogen uptake by seaweed...
in terms of parameters essential to design intensive mariculture ponds. Secondly, the control of the pond water quality for the practical shrimp culture batch was simulated by simple calculation based on material balance of ammonia-nitrogen with parameters obtained from the experiments. This calculation allowed a discussion about the feasibility of this water quality control method.

1. Performance of Ammonia-Nitrogen Uptake by Seaweed

1.1 Experimental

We selected sterile Ulva sp. as a model seaweed, as this species is distributed worldwide. It was collected in August, 2005 from Kanazawa Bay (Yokohama, Japan, 35°20′32″N, 139°38′32″E). The principal properties of this seaweed were shown in the previous paper (Sato et al., 2006a). Commercial sea salt (Akuazarutus, Nisseisangyokabushikigaisha (a joint-stock company)) was used to prepare the culture solution of artificial seawater. NH₄Cl (special grade, Wako Pure Chemical Industries, Ltd.) and NaH₂PO₃ (special grade, Wako Pure Chemical Industries, Ltd.) were used as sources of ammonia-nitrogen (ammonia-N) and phosphorus in the culture solution, respectively.

The collected biomass was pretreated and preserved in a ready-made glass aquarium containing 5.0 × 10⁻³ m³ of artificial seawater, as mentioned in the previous paper (Sato et al., 2006a). The dry mass of the initial seaweed for the uptake run was determined from the fresh mass with the ratio of fresh and dry masses of the seaweed, which was measured beforehand. The apparatus for the uptake experiment is schematically shown in Figure 1. A metal halide lamp (EYE Clean-Ace M400DL/BUDP, Iwasaki Electric Co., Ltd.) provided light for the culture system in a stainless steel tank (1.0 × 10⁻³ m³, 0.24 m in i.d. × 0.24 m in height). Photosynthetic photon flux (PPF) of light was measured at several points of the solution surface by a quantum meter (Model QMSS-SUN, Apcie Instruments Inc.) to fix PPF by adjusting the distance between the lamp and the surface. The culture solution was agitated by aeration and was kept at specified water temperature. At first, the seaweed was acclimatized for more than 0.5 h in the culture solution under the conditions for the uptake run without ammonia-N. After the acclimatization, the condensed NH₄Cl solution started to be supplied by a micro-plunger pump for HPLC (LC10-ADVP, Shimadzu Corp.) to the culture solution at the specified flow rate. In this manner, the generation of ammonia-N in the real shrimp culture pond was simulated in the tank. A portion of the culture solution was sampled and analyzed over time to obtain the time course of ammonia-N contents in the solution. The amount of NH₄Cl solution supplied to the tank by the pump and that of the culture solution sampled from the tank for analysis were so small and negligible relative to the total amount of the culture solution in the tank. The concentration of total ammonia-N (in the forms of NH3 and NH₄⁺) was determined by the indophenol blue method (Japan Meteorological Agency, 1970).

The main conditions in the uptake runs are summarized in Table 1. The biomass density in the culture, the flow rate of the NH₄Cl solution pumped to the tank, and the existence of light varied in the uptake runs. The light of 1800 μmol m⁻² s⁻¹ and the water temperature of 30 ± 2°C were selected considering the conditions of intensive shrimp culture farms in tropical regions (Sakuratani et al., 2002).

1.2 Results and discussion

When seaweed is introduced in an intensive aquaculture pond, the material balance of ammonia-N in a unit volume of pond water can be described as,

\[
\frac{dC_{\text{TAN}}}{dt} = r_{\text{TAN}} - \rho_u \pi_{u,\text{TAN}}
\]

where \(C_{\text{TAN}}\) is the total ammonia-N concentration in the pond, \(r_{\text{TAN}}\) is the rate of ammonia-N generation in a unit volume of the pond water, \(\rho_u\) is the culture density of seaweed, and \(\pi_{u,\text{TAN}}\) is the rate of ammonia-N uptake by a unit dry mass of the seaweed. This \(\pi_{u,\text{TAN}}\) is

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V [\text{m}^3])</td>
<td>5.0 × 10⁻³</td>
</tr>
<tr>
<td>Salinity of culture solution ([\text{kg m}^{-3}])</td>
<td>30</td>
</tr>
<tr>
<td>(\rho_u [\text{kg DM m}^{-3}])</td>
<td>0–1.3</td>
</tr>
<tr>
<td>Concentration of ammonia-N in (\text{NH}_4\text{Cl}) solution to be fed ([\text{kg-N m}^{-3}])</td>
<td>0.17</td>
</tr>
<tr>
<td>Flow rate of (\text{NH}_4\text{Cl}) solution to be fed ([\text{m}^3 \text{h}^{-1}])</td>
<td>7 × 10⁻¹–3 × 10⁻³</td>
</tr>
<tr>
<td>(r_{\text{TAN}} [\text{kg-N m}^{-3} \text{h}^{-1}])</td>
<td>2 × 10⁻¹–1 × 10⁻¹</td>
</tr>
<tr>
<td>(C_{\text{pp}} [\text{kg-P m}^{-3}])</td>
<td>1 × 10⁻¹</td>
</tr>
<tr>
<td>PPF ([\text{μmol m}^{-2} \text{s}^{-1}])</td>
<td>0, 1.8 × 10³</td>
</tr>
<tr>
<td>(T [\text{°C}])</td>
<td>30 ± 2</td>
</tr>
</tbody>
</table>
represented using the Michaelis–Menten model with uncompetitive inhibition as,

$$\pi_{a,TAN} = \frac{v_{\text{max}}C_{TAN}}{K_M + (1 + \alpha)C_{TAN}}$$ (2)

where $v_{\text{max}}$, $K_M$ are the constants in Michaelis–Menten equation incorporating the constants related to ammonia ionization equilibrium in the aqueous phase, and $\alpha$ is the inhibitor constant (Fujita, 1985; Runcie et al., 2003; Sato et al., 2006a). $\pi_{a,TAN}$ increases with $C_{TAN}$ and approaches,

$$\pi_{a,TAN,\text{max}} = \lim_{C_{TAN}\to\infty} \frac{v_{\text{max}}C_{TAN}}{K_M + (1 + \alpha)C_{TAN}} \equiv \frac{v_{\text{max}}}{1 + \alpha}$$ (3)

When the inhibitor constant, $\alpha$, increases, namely, the inhibitory effect is intensified, $\pi_{a,TAN}$ becomes small (Fujita, 1985; Runcie et al., 2003; Sato et al., 2006a). Equation (2) is substituted into Eq. (1) to give,

$$\frac{dC_{TAN}}{dt} = r_{TAN} - \rho_u \frac{v_{\text{max}}C_{TAN}}{K_M + (1 + \alpha)C_{TAN}}$$ (5)

In order to keep $C_{TAN}$ expressed by this equation lower than a certain permissible level,

$$\frac{dC_{TAN}}{dt} \leq 0$$ (6)

that is,

$$r_{TAN} \leq \rho_u \frac{v_{\text{max}}C_{TAN}}{K_M + (1 + \alpha)C_{TAN}}$$ (7)

should hold, finally.

Here, $r_{TAN}$, $\rho_u$, and $A_u$ are assumed to be constant, for simplicity. Two conditions are required so that Eq. (7) holds. One is that,

$$r_{TAN} < \rho_u \frac{v_{\text{max}}C_{TAN}}{C_{TAN,max}}$$ (8)

and the other is that $\alpha$ does not increase with time,

$$\frac{d\alpha}{dt} \leq 0$$ (9)

Equation (8) can readily be satisfied by keeping $\rho_u$ at a sufficient value. Since $\alpha$ increases with the amount of ammonia-N in a seaweed cell, $C'_{\text{TAN}}$ (Sato et al., 2006a), $C'_{TAN}$ should not increase so as to meet the condition of Eq. (9):

$$\frac{dC'_{TAN}}{dt} \leq 0$$ (10)

$\pi_{a,TAN}$ can be written also based on the material balance in seaweed with the assimilation rate of ammonia-N in the cells, $\pi_{a,TAN}$, as,

$$\pi_{a,TAN} = \frac{dC'_{TAN}}{dr} + \pi_{a,TAN}$$ (11)

From this equation and Eq. (10),

$$\pi_{a,TAN} \leq \pi_{a,TAN}$$ (12)

should hold, that is, the assimilation rate should not be lower than the uptake rate. This inequality is combined with Eq. (2) to obtain,

$$C_{TAN} \leq \frac{K_M\pi_{a,TAN}}{v_{\text{max}} - \pi_{a,TAN}(1 + \alpha)}$$ (13)

$$\equiv C_{TAN,\text{lim}}$$ (14)

Consequently, if $C_{TAN}$ is prevented from exceeding a certain limit concentration, $C_{TAN,\text{lim}}$, $C_{TAN}$ can be kept at any concentration under $C_{TAN,\text{lim}}$ for any $r_{TAN}$ by selecting any appropriate value of $\rho_u$.

If Eqs. (8), (13), and (14) are satisfied, Eqs. (1) and (5) in a steady state are,

$$0 = r_{TAN} - \rho_u \pi_{a,TAN,\text{st}}$$ (15)

$$= r_{TAN} - \rho_u \frac{v_{\text{max}}C_{TAN,\text{st}}}{K_M + (1 + \alpha)C_{TAN,\text{st}}}$$ (16)

with the ammonia-N concentration at this steady state, $C_{TAN,\text{st}}$, and, then,

$$C_{TAN,\text{st}} = \frac{K_Mr_{TAN}}{\rho_u v_{\text{max}} - (1 + \alpha)r_{TAN}}$$ (17)

Figure 2 shows examples of the time courses of $C_{TAN}$ predicted from the above equations, schematically. When Eqs. (8), (13), and (14) hold, $C_{TAN}$ increases up to $C_{TAN,\text{lim}}$, asymptotically, the system becomes steady (curve (a) in the figure), and could be kept at a constant value. Otherwise, once that $C_{TAN}$ exceeds $C_{TAN,\text{lim}}$, $C_{TAN}$ continues to increase with time (curve (b)) and cannot be controlled any longer.

In the first, we confirmed by the runs using no seaweed that the ammonia evaporation from the solution into the atmosphere and the ammonia oxidization...
to nitric or nitrous ions were negligible. There was no effect of $\rho_u$ on ammonia-N uptake in the range of this work (data are not shown).

Figure 3 shows typical examples of the time courses of ammonia-nitrogen concentration in the uptake run with continuous and constant ammonia-nitrogen supply (dashed line indicates ammonia-nitrogen concentration without seaweed; “X” denotes $C_{\text{TAN}}$ exceeding $C_{\text{TAN,lim}}$).

![](image)

**Figure 2** Quantitative prediction of time courses of ammonia-nitrogen concentration in culture solution, $C_{\text{TAN}}$, with constant rate of ammonia-nitrogen generation

<table>
<thead>
<tr>
<th>$\rho_u$ [kgDM m$^{-3}$]</th>
<th>PPF [µmol m$^{-2}$ h$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36</td>
<td>1800</td>
</tr>
<tr>
<td>0.66</td>
<td>1800</td>
</tr>
<tr>
<td>1.23</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 3** Examples of the time courses of ammonia-nitrogen concentration in the uptake run with continuous and constant ammonia-nitrogen supply (dashed line indicates ammonia-nitrogen concentration without seaweed; “X” denotes $C_{\text{TAN}}$ exceeding $C_{\text{TAN,lim}}$)

to nitric or nitrous ions were negligible. There was no effect of $\rho_u$ on ammonia-N uptake in the range of this work (data are not shown).

Figure 3 shows typical examples of the time courses of ammonia-N concentration in the uptake runs with continuous ammonia-N supply. Under several conditions, the ammonia-N concentration increased up to constant concentrations asymptotically and the system attained steady states, as predicted in curve (a) given in Figure 2. Seaweed could keep the ammonia-N concentration constant even without light. Ammonia-N uptake by seaweed without light was reported also in previous studies (D’Elia and DeBoer, 1978; Neori et al., 1991; Sato et al., 2006a). This property of seaweed is advantageous, because ammonia-N must be removed also at night without light in shrimp farms, which are usually located in the open in the developing region. The highest $C_{\text{TAN,lim}}$ was about 0.1 in these runs.

On the other hand, when $r_{\text{TAN}}$ was higher, $\rho_u$ was low, or there was no light, the ammonia-N concentration continued to increase and no steady state could be obtained in some cases. When the ammonia-N concentration exceeded $C_{\text{TAN,lim}}$, $C'_{\text{TAN}}$ and $\alpha$ started to increase, the inhibition in seaweed became intense, and the uptake rate decreased (Fujita, 1985; McGlathery et al., 1996; Runcie et al., 2003; Sato et al., 2006a). A smaller assimilation rate, $\pi_{u,TAN}$ in the case without light may make $C_{\text{TAN,lim}}$ lower as represented by Eqs. (13) and (14). This result agreed with our previous prediction that light enhances the assimilation rate (Sato et al., 2006a).

From these results, although the definite values of $C_{\text{TAN,lim}}$ could not be determined for both cases with and without light, the ranges of $C_{\text{TAN,lim}}$ were expected to be more than $0.1 \times 10^{-3}$ kg-N m$^{-3}$ for both cases, according to Eqs. (13) and (14).

Authors reported previously that $K_m$ of the sterile Ulva sp. was $8.1 \times 10^{-3}$ kg-N m$^{-3}$ and that $\alpha$ even in the case of high $C'_{\text{TAN}}$ was 1.6 (Sato et al., 2006a). In the runs where steady states could be obtained, $C_{\text{TAN}}$ and $\alpha$ were so small that,

$$ (1 + \alpha)C_{\text{TAN}} \leq K_m $$  \hspace{1cm} (18)

holds. Equation (2), thus, became,

$$ \pi_{u,TAN} = A_u C_{\text{TAN}} $$  \hspace{1cm} (19)

where $A_u$ is the affinity between ammonia-N and its carrier protein in seaweed cell membrane generally defined and represented as follows:

$$ A_u = \lim_{C_{\text{TAN}} \to 0} \frac{d\pi_{u,TAN}}{dC_{\text{TAN}}} $$  \hspace{1cm} (20)

$$ = \frac{v_{\text{max}}}{K_m} $$  \hspace{1cm} (21)

In the steady state, the combination of Eqs. (15) and (19) gave,

$$ \pi_{u,TAN,st} = \frac{r_{\text{TAN}}}{\rho_u} $$  \hspace{1cm} (22)

$$ = A_u C_{\text{TAN,st}} $$  \hspace{1cm} (23)
According to these equations, \( \pi_{u,TAN,st} \), namely, \( r_{TAN}/\rho_{u} \), is plotted against \( C_{TAN,st} \) in Figure 4. Although plots of the results were not on a straight line and the effects of light and others were not clarified probably due to fluctuations of the results, the average value of \( A_{u} \) was found to be around 3.3 m\(^3\) kgDM\(^{-1}\) h\(^{-1}\) from the slope of the line roughly drawn from the origin of the coordinate axes.

2. Water Quality Control by Seaweed for Intensive Shrimp Culture Ponds

2.1 Calculation

A calculation was carried out to simulate the water quality control by Ulva sp. for the closed system of a culture pond of Penaeus monodon (giant tiger prawn), which is one of the major shrimps cultured in intensive shrimp farms in developing countries.

Equation (15) of the material balance of ammonia-N in the pond was used for the simulation with the following assumptions: The system of the culture pond became steady quite rapidly and changed maintaining the steady state; only uptake by the seaweed, Ulva sp., lowered the amount of ammonia-N in the pond. A principal source for ammonia-N generated in the culture pond is the feed for shrimps. Supposing that all of the nitrogen that was not assimilated by shrimps became ammonia-N, the rate of ammonia-N generation in the pond, \( r_{TAN} \), was estimated by,

\[
r_{TAN} = m_{s} \xi \phi_{s} x_{N}(1 - \eta)
\]

(24)

Fig. 4 Relation between the ammonia-nitrogen concentration and the uptake rate in the steady state, \( \pi_{u,TAN,st} \)

Table 2 Parameters used in calculation for concentration of ammonia-nitrogen in intensive shrimp culture ponds

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average body mass of postlarvae, ( m_{s,0} ) [kgFM]</td>
<td>( 1 \times 10^{-3} )</td>
</tr>
<tr>
<td>Culture density of shrimps at initial, ( \phi_{s,0} ) [m(^{-3})]</td>
<td>40</td>
</tr>
<tr>
<td>Final survival fraction [( \xi )]</td>
<td>0.8</td>
</tr>
<tr>
<td>Mass fraction of nitrogen in feed, ( x_{N} ) [( - )]</td>
<td>0.056</td>
</tr>
<tr>
<td>Fraction of nitrogen assimilated by shrimps, ( \eta ) [( - )]</td>
<td>0.3</td>
</tr>
<tr>
<td>Affinity, ( A_{u} ) [m(^{3}) kgDM(^{-1}) h(^{-1})]</td>
<td>3.3*</td>
</tr>
<tr>
<td>Specific growth rate, ( \mu_{u} ) [d(^{-1})]</td>
<td>0.08**</td>
</tr>
<tr>
<td>( C_{TAN,lim} ) [kg-N m(^{-3})]</td>
<td>( 1.0 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

*From the experimental results
**Neori et al. (1991)

Fig. 5 Average mass of a giant tiger prawn and feeding schedule in a culture batch (Lin, 1988)

where \( m_{s} \) is the average mass of a shrimp, \( \xi \) is the ratio of the feeding rate relative to the average body mass of a shrimp, \( \phi_{s} \) is a culture density of shrimps, \( x_{N} \) is the mass fraction of the nitrogen element in the feed for the shrimp, and \( \eta \) is the fraction of nitrogen assimilated by shrimps. Figure 5 and Table 2 show the values of parameters necessary for the simulation. The time course of the average mass of a giant tiger prawn in a culture batch as shown in Figure 5 (Lin, 1988) was adopted as \( m_{s} \) with \( 1 \times 10^{-3} \) kgFM of the mass of a postlarvae, \( m_{s,0} \) in Table 2. The effects of the ammonia-N concentration of the pond and the feeding rate on \( m_{s} \) were ignored. The feeding rate is decided based on the average mass of a shrimp. Since the feeding rate of 0.8 that is recommended by feed manufactures in Taiwan (Lin, 1988) is employed in most shrimp farms, this value was used in this study. Thus the fixed feeding rate, \( \xi \), is taken as is shown in Figure 5. A final survival fraction of shrimps depends largely on
the way of cultivation and the economic strategy in individual farms. According to the information from a shrimp farm in the Philippines, the final survival fraction can reach high, more than 0.8, in the culture batch with postlarvae of relatively large averaged body mass, $1 \times 10^{-4}$ kgFM as above. We supposed that the survival fraction decreased linearly from unity at start to 0.8 at end in a culture batch. With this survival fraction and the initial shrimp density ($\phi_s,0$) of $40 \times 10^{-3}$, we estimated the shrimp density, $\phi_s$. Feed for giant tiger prawns contains proteins of 0.35 in mass fraction and the content of nitrogen element in the protein is about 0.16 at highest. The mass fraction of the nitrogen element in the feed, $x_N$, was, thus, fixed at 0.056. According to the previous study on the material balance of nitrogen in a closed shrimp culture pond, shrimps assimilate about 0.3 of nitrogen contained in the feed provided for the pond (Thakur and Lin, 2003). Neori et al. (1991) reported that the growth of seaweed could be represented by,

$$\rho_u = \rho_{u,0} e^{\mu_u t}$$

(25)

with a specific growth rate of seaweed, $\mu_u$, and that $\mu_u$ for Ulva lactuca in fish effluent water was 0.08 d$^{-1}$ at minimum. These were substituted for those for Ulva sp. on trial. The effect of the culture density of seaweed and the concentration of ammonia-N in the pond on the growth rate of seaweed were neglected here, although the density may affect the seaweed growth. Equation (23) of the ammonia-N uptake rate by seaweed was used for the simulation. The averaged affinity, $A_u$, obtained from the experiments was used here as given in Table 2. From the experimental results, $C_{TAN,lim}$ was $1 \times 10^{-3}$ kg-N m$^{-3}$. This is sufficiently lower than the ammonia-N concentration of a generally safe level, about 0.8–1.0 $\times 10^{-3}$ kg-N m$^{-3}$, in the ponds. Table 3 gives the seaweed conditions for simulation. The seaweed density and the way of seaweed removal from the pond were varied.

With these equations, parameters, assumptions, and conditions, calculation was carried out to obtain the time course of ammonia-N concentration, $C_{TAN,st}$, during the culture batch.

### 2.2 Results and discussion

Figure 6 shows the time course of the average rate of ammonia-N generation in the pond during the culture batch estimated by Eq. (24), $r_{TAN}$. There were multiple peaks in the time course, since the feeding rate, $\xi$, decreased discontinuously with an increasing average mass of a shrimp, as shown in Figure 5.

Figure 7 shows the time courses of $C_{TAN,st}$ in the pond, where $\rho_u$ increased with seaweed proliferation from a specified value of $\rho_{u,0}$ at start and seaweed was not removed until the end of the batch (CAL1). $C_{TAN,st}$ did not exceed $C_{TAN,lim}$ throughout the batches with a relatively low initial seaweed density, more than 0.01 kgDM m$^{-3}$, since the seaweed proliferated exponentially, as Eq. (25). The $C_{TAN,st}$ decreased with increasing initial seaweed density, $\rho_{u,0}$. However, this steep proliferation of seaweed may be a disadvantage interfering the shrimp culture operation rather than being an advantage for controlling of ammonia-N concentration in the pond. The seaweed density at the end of the batch was 136 kgDM m$^{-3}$ even in the case of $\rho_{u,0} = 0.01$ kgDM m$^{-3}$, for example. The seaweed density should, therefore, be adjusted by removing proliferate seaweed at proper intervals during the batch in the practical operation.

Table 3 Conditions for the calculation of the concentration of ammonia-nitrogen in intensive shrimp culture ponds

<table>
<thead>
<tr>
<th>Run</th>
<th>CAL1</th>
<th>CAL2</th>
<th>CAL3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{u}$ [kgDM m$^{-3}$]</td>
<td>0.005–0.04 ($t = 0$ d)</td>
<td>0.1–1.6</td>
<td>0.2 ($0 \leq t &lt; 49$ d), 0.4 ($49 \leq t$)</td>
</tr>
<tr>
<td>Seaweed removal</td>
<td>Only at the end of batch</td>
<td>Weekly to keep $\rho_u$</td>
<td>Weekly to keep $\rho_u$</td>
</tr>
</tbody>
</table>

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With these equations, parameters, assumptions, and conditions, calculation was carried out to obtain the time course of ammonia-N concentration, $C_{TAN,st}$, during the culture batch.

### 2.2 Results and discussion

**Figure 6** Daily average of the ammonia-nitrogen generation rate in the culture pond during a culture batch
The concentration of ammonia-N could be kept sufficiently low enough to cultivate shrimps in the ponds also in this case. The averaged concentration of ammonia-N during the batch was $3.4 \times 10^{-5}$ kg-N m$^{-3}$.

Table 4 summarizes the productions of shrimps and seaweed under the conditions of Figure 9 in a pond of $2.5 \times 10^3$ m$^3$, 50 m square with 1 m depth. The final shrimp production of $2.7 \times 10^3$ kgFM was obtained from the initial postlarvae input of 10 kgFM with the total feed input of $6.9 \times 10^3$ kgFM. The feed conversion ratio was 2.5. A relatively large amount of seaweed, $4.0 \times 10^4$ kgFM, was obtained in the culture batch, which is about 20 times of the initial input. Hitherto, seaweed has been used as a fertilizer all over the world. Lately, it is successfully used as additives to feed for chickens and fishes (Notoya, 2001), as well. The obtained seaweed can be a profitable by-product from the shrimp culture pond.

Figure 9

Time course of $C_{\text{TAN,sT}}$ in the case where $\rho_u$ was specified according to the growth of shrimp

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Conclusion

Based on the mechanism of ammonia-nitrogen uptake by seaweed, it was predicted that the ammo-
Nomenclature

- $V$ = volume of culture system [m$^3$]
- $v$ = time [h or d]
- $T$ = temperature [°C]
- $N$ = number of shrimps
- $s$ = averaged fresh mass of shrimp [kgFM]
- $u$ = culture density of seaweed [kgDM m$^{-1}$]
- $u,TAN$ = rate of total ammonia-nitrogen uptake by seaweed
- $a,TAN$ = rate of total ammonia-nitrogen assimilation by seaweed
- $TAN$ = concentration of total ammonia-nitrogen
- $P,0$ = initial concentration of phosphoric acid-phosphoprotein in seaweed cell membrane [m$^3$ kgDM$^{-1}$]
- $d$ = duration of ammonia and carrier penetration in seaweed cell membrane [h or d]
- $A_s$ = affinity between ammonia-nitrogen and carrier protein in seaweed cell membrane [m$^3$ kgDM$^{-1}$ h$^{-1}$]
- $C_{PS}$ = initial concentration of phosphoric acid-phosphorus [kg-P m$^{-3}$]
- $C_{TAN}$ = concentration of total ammonia-nitrogen [kg-N m$^{-3}$]
- $C_{TAN,max}$ = limit concentration of total ammonia-nitrogen defined by Eq. (14) [kg-N m$^{-3}$]
- $C_{TAN,sta}$ = concentration of total ammonia-nitrogen at a steady state [kg-N m$^{-3}$]
- $C_{TAN}'$ = amount of total ammonia-nitrogen contained in seaweed of unit dry mass [kg-N kgDM$^{-1}$]
- $K_M = Michaelis–Menten constant [kg-N m$^{-3}$]
- $m_s$ = averaged fresh mass of shrimp [kgFM]
- $r_{TAN}$ = rate of total ammonia-nitrogen generation [kg-N m$^{-3}$ h$^{-1}$]
- $T$ = temperature [°C]
- $t$ = time [h or d]
- $V$ = volume of culture system [m$^3$]
- $v_{max}$ = maximum rate of ammonia-nitrogen uptake by seaweed in the Michaelis–Menten equation
- $x_{N}$ = mass fraction of nitrogen in feed of shrimp [-]
- $\alpha$ = inhibitor constant [-]
- $\eta$ = fraction of nitrogen assimilated by shrimps [-]
- $\mu_s$ = specific growth rate of seaweed in Eq. (25) [d$^{-1}$]
- $\xi$ = mass ratio of daily feed relative to the average body mass of shrimp [d$^{-1}$]
- $\pi_{s,TAN}$ = rate of total ammonia-nitrogen assimilation by seaweed [kg-N kgDM$^{-1}$ h$^{-1}$]
- $\pi_{TAN}$ = rate of total ammonia-nitrogen uptake by seaweed [kg-N kgDM$^{-1}$ h$^{-1}$]
- $\pi_{s,TAN,max}$ = maximum rate of total ammonia-nitrogen uptake by seaweed defined by Eq. (3) [kg-N kgDM$^{-1}$ h$^{-1}$]
- $\pi_{s,TAN,sta}$ = rate of total ammonia-nitrogen uptake by seaweed at a steady state [kg-N kgDM$^{-1}$ h$^{-1}$]
- $\rho_s$ = culture density of seaweed [kgDM m$^{-3}$]
- $\phi$ = culture density of shrimp: the number of shrimps in a unit volume of pond [m$^{-3}$]

Literature Cited


