Aquaculture Research, 1999, **30,** 923–927

SHORT COMMUNICATION

Nitrogen recovery from shrimp pond effluent: dissolved nitrogen removal has greater overall potential than particulate nitrogen removal, but requires higher rates of water exchange than presently used

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The loss of feed nutrients is widely seen as a key environmental management problem in intensive shrimp farming and other forms of intensive aquaculture (Hopkins, Sandifer & Browdy 1995). Only 20–40% of feed nitrogen, for example, is incorporated into shrimp tissue, while the remainder is lost to the pond and, ultimately, the wider environment (Philips, Lin & Beveridge 1993). Nitrogen waste presents particular problems because some dissolved N components are toxic to aquatic animals and must be maintained at low concentrations in the production pond itself.

In intensive pond culture systems, the bulk of wasted nitrogen (typically 90%) enters the water as ammonia (total ammonia nitrogen, TAN), through either direct excretion by animals or ammonification of organic N in wasted feed and faeces (Hargreaves 1998). Owing to the relatively low rates of water exchange commonly used in shrimp pond systems, pond internal processes play an important role in TAN transformations and determine the fate of N wastes, including the form and amount of N discharged during water exchange. Phytoplankton uptake dominates TAN transformations under normal pond conditions, and sedimentation of the resulting particulate N effectively removes it from the water column (Lorenzen, Struve & Cowan 1997; Hargreaves 1998).

Intensive pond culture systems with N recovery

The recovery and productive use of wasted N can reduce the environmental impact of intensive aquaculture and increase its ecological efficiency. A variety of integrated aquaculture systems with waste recovery have been proposed and operated on a pilot scale (Hopkins *et al.* 1995). Most of these systems are based on the recovery of nutrients from pond effluent, using dedicated treatment ponds integrated into either throughflow or recirculation systems. The recovery and use of nutrients from production pond sediments is problematic, because of the high salt and low organic content of shrimp pond sediment (Briggs & Funge-Smith 1994). Moreover, N locked into sediments may be resuspended and discharged when the pond is drained for harvesting. The occasional nature of harvest discharges precludes effective nutrient recovery from such effluents. To maximize N recovery, it is therefore desirable to minimize N sedimentation in the first place and discharge as much wasted N as possible into treatment ponds.

There are three main options for N recovery from pond effluent: (1) uptake of dissolved N (mainly TAN) by aquatic plants (e.g. Ellner, Neori, Krom, Tsai & Easterling 1996); (2) uptake of particulate N (mainly phytoplankton) by filter feeding animals (e.g. Jones & Preston 1999); (3) uptake of mixed (particulate and dissolved) N wastes in plant beds (e.g. Brown & Glenn 1999).

The effectiveness of the above options in removing the respective target forms of N from effluent has been established experimentally (see Hopkins *et al.* 1995 and references above). However, the overall potential for N recovery in an integrated system depends in the first place on the proportion of wasted N discharged into the treatment pond and thereby made available for recovery. Both the overall amount and the forms of N discharged are determined by the operating characteristics of the intensive production pond, in particular TAN input (i.e. farming intensity) and the rate of water exchange (Lorenzen *et al.* 1997). This paper explores the implications of pond operating characteristics for N recovery potential.

Nitrogen dynamics model predictions of recovery potential

The present study uses a nitrogen dynamics model for intensive pond culture, which has been described in detail and calibrated for Thai commercial shrimp farms by Lorenzen *et al.* (1997). In accordance with nutrient budgets and water quality data for the Thai shrimp farms used in model calibration, it is assumed that the bulk of N input into the pond is derived from feed and enters the water column as TAN. The model describes mathematically the transformations of TAN by phytoplankton uptake and nitrification, and the loss of N from the production pond through sedimentation, discharge and volatilization. The model parameter values used in the present study are those giving the best description of observed dynamics in the low-intensity farm (see Lorenzen *et al.* 1997) and are listed in Table 1.

Pond culture systems with effective nitrogen waste removal must satisfy two criteria: they must maintain TAN concentrations in the production pond within acceptable limits (e.g. $< 1.0\ \mathrm{mg\,L^{-1}}$), and they must deliver as much waste nitrogen as possible to the treatment pond. Hence, model predictions are analysed in terms of both these criteria.

Model predictions of pond TAN and the fate of TAN inputs in relation to input levels and water exchange are summarized in Fig. 1. Pond TAN (Fig. 1a) shows patterns discussed in detail by Lorenzen *et al.* (1997). Phytoplankton uptake maintains low ($< 1\ \mathrm{mg\,L^{-1}}$) pond TAN levels for inputs of less than $1\ \mathrm{mg\,L^{-1}\,day^{-1}}$ (corresponding to a standing stock of about 6.6 tonnes $\mathrm{ha^{-1}}$ harvestable size shrimp). Water exchange of up to about $0.4\ \mathrm{day^{-1}}$ at these TAN input levels is predicted to result in a moderate increase in pond TAN, because of reduced phytoplankton uptake, which is not fully balanced by increased dilution. TAN inputs above $1\ \mathrm{mg\,L^{-1}\,day^{-1}}$ exceed the phytoplankton uptake capacity and result in high pond TAN levels. Water exchange at these input levels always reduces pond TAN, but high exchange rates are required to achieve a TAN concentration below $1\ \mathrm{mg\,L^{-1}}$.

The fate of nitrogen waste as a proportion of TAN inputs is shown in Fig. 1b–d. Discharge of dissolved inorganic nitrogen (mainly TAN) increases rapidly with water exchange at all input levels; it is the dominant fate of N at exchange rates above $0.3\ \mathrm{day^{-1}}$ and accounts for more than 80% of N waste at exchange rates above $0.6\ \mathrm{day^{-1}}$. Sedimentation (Fig. 1c) is the dominant fate of N at low water exchange and moderate TAN inputs, but becomes negligible at exchange rates above $0.4\ \mathrm{day^{-1}}$. Discharge in particulate form (Fig. 1d) is never a dominant fate of nitrogen waste and is significant only in a relatively narrow region of moderate TAN input and water exchange (with a maximum of 24% at a TAN input of $0.45\ \mathrm{mg\,L^{-1}\,day^{-1}}$ and water exchange of $0.2\ \mathrm{day^{-1}}$).

Figure 1e provides a schematic synthesis of limits imposed on operating characteristics by the resulting production pond TAN concentration, and of the fate of wasted N within the possible operating region.

These results indicate that systems removing dissolved inorganic nitrogen (such as seaweed biofilters) have the greatest overall recovery potential and can accommodate high TAN inputs in the production ponds, but require high rates of water exchange. Systems removing particulate N have a much lower overall recovery potential because the proportion of waste nitrogen discharged in this form is small, being limited by sedimentation at low water exchange rates and by insufficient phytoplankton uptake at higher

Table 1 Model parameter values and sensitivity analysis of the proportion of nitrogen discharged in particulate form

Parameter	Default value	Sensitivity of proportion particulate	Proportion of particulate discharge achievable by manipulation of sensitive parameters to the value indicated, and corresponding optimal operating conditions			
			Parameter value	Proportion particulate (%)	TAN input (mg L^{-1} day^{-1})	Water exchange (day^{-1})
Sedimentation rate s (day^{-1})	0.35	− 1.6	0.1	61	0.51	0.25
Phytoplankton growth rate g_{max} (day^{-1})	1.33	+ 1.5	3.0	52	1.08	0.59
Extinction from non-Chl k_{other} (m^{-1})	2.60	− 1.0	1.0	39	0.66	0.36
Saturation light intensity I_{sat} (E m^{-2} day^{-1})	37.6	− 0.9	20	34	0.63	0.29
Surface light intensity I_0 (E m^{-2} day^{-1})	40.0	+ 0.8	60	31	0.57	0.26
Depth z (m)	1.0	+ 0.3				
Nitrogen-to-Chl ratio c	8.9	+ 0.3				
Nitrogen half-saturation Ks_N (mg L^{-1})	0.095	− 0.3				
Volatilisation rate v (day^{-1})	0.17	− 0.1				
Phosphorus half-saturation Ks_P (mg l^{-1})	0.0009	0.0				
Nitrification rate n (day^{-1})	0.91	0.0				

Sensitivity is measured as the relative change in the proportion of N waste discharged in particulate form, divided by the underlying relative change in the parameter. Also given is the maximum proportion of particulate N discharge achievable by manipulating the parameter within realistic limits, and the corresponding optimal operating conditions (TAN input and water exchange).

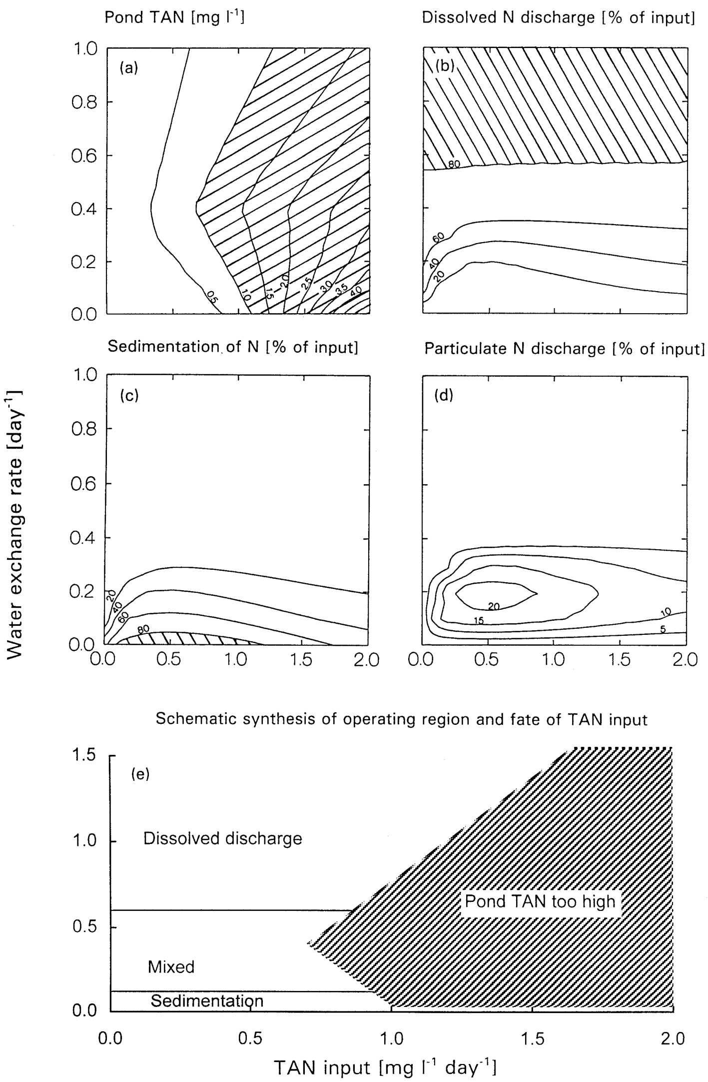

Figure 1 Model predictions of production pond TAN concentrations (a) and fate of nitrogen wastes (b–d) in relation to TAN input and water exchange rate. A schematic synthesis is given in (e).

exchange rates. Also, the use of such systems is restricted to TAN input levels not exceeding the phytoplankton uptake capacity.

Options for increasing the proportion of N discharged in particulate form

Would it be possible to increase the proportion of N discharged in particulate form in order to make recovery systems based on particulate removal more effective? The sensitivity of the proportion of N discharged in particulate form to different model parameters is analysed in Table 1. Also indicated are the maximum proportions of particulate N discharge achievable through manipulation of sensitive parameters within realistic limits, and the respective optimal operating conditions. Reductions in the plankton sedimentation rate, extinction from non-chlorophyll sources and the saturation light intensity or increases in plankton growth rate or surface light intensity are expected to increase the proportion of N discharged in particulate form to between 31% and 61%. In all cases, the optimal operating conditions would occur at moderately higher levels of both TAN input and water exchange than in the baseline case.

Only the extinction from non-chlorophyll sources can be manipulated relatively easily, for example through the use of aeration techniques that prevent erosion of the pond banks and bottom (Boyd 1995). Manipulations of the phytoplankton community towards species with a low sedimentation rate, high growth rate and high light sensitivity are not a practical option at present. However, in-depth studies of phytoplankton dynamics in shrimp ponds (e.g. Burford & Glibert 1999) may eventually allow a greater degree of control over key parameters.

Present operating characteristics of commercial shrimp farms and implications for recovery potential

Commercial, intensive shrimp farms typically produce between 2 and 12 tonnes ha^{-1} $crop^{-1}$ (implying maximum TAN input rates of 0.3–1.8 mg L^{-1} day^{-1}) and exchange water at rates between 0.05 and 0.3 day^{-1}, although experimental systems sometimes operate with much higher production and water exchange rates (Hopkins, Hamilton, Sandifer, Browdy & Stokes 1993; Kongkeo 1997). Hence, presently used systems deposit the bulk of waste nitrogen in sediments (partly resuspended and discharged at harvest). The remainder is largely discharged with routine water exchange, as a mixture of dissolved and particulate N. Increased water exchange (>0.6 day^{-1}) would minimize N sedimentation in the production pond and allow recovery of the bulk of wasted N in treatment systems targeted at dissolved N removal (e.g. seaweed biofilters).

Discussion

The results presented here have been generated using a model developed and calibrated for Thai commercial shrimp farms. Other farms may show quantitatively different relationships between operating characteristics and N discharge, but the overall qualitative pattern is expected to be similar in all farms in which the bulk of N input is derived from feed, and waste enters the water column as TAN.

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