

Impact of farming intensity and water management on nitrogen dynamics in intensive pond culture: a mathematical model applied to Thai commercial shrimp farms

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Abstract

A mathematical model is used to investigate the impact of farming intensity and water management on nitrogen dynamics in the water column of intensive aquaculture ponds. The model describes the input of ammonia, its assimilation by phytoplankton or nitrification, and the loss of nitrogen through sedimentation, volatilization, and discharge. The model is calibrated for two commercial shrimp (*Penaeus monodon* Fabricius) farms in Thailand. Assimilation by phytoplankton with subsequent sedimentation or discharge is the principal process of ammonia removal. When inputs of ammonia exceed the algal assimilation capacity (carrying capacity), nitrification and volatilization of excess ammonia become significant. Carrying capacity is negatively affected by non-chlorophyll turbidity, and was estimated as $6 \text{ t ha}^{-1} \text{ cycle}^{-1}$ at a non-chlorophyll extinction of 2.6 m^{-1} . In ponds managed within their carrying capacity, ammonia concentrations are lowest at no water exchange, reach a maximum at exchange rates between 0.2 and 0.4 day^{-1} , and decline again at higher rates. When the carrying capacity is exceeded, excess ammonia concentrations decline continuously with increasing water exchange. Average exchange rates used in intensive shrimp farms (up to 0.2 day^{-1}) reduce

phytoplankton abundance and sedimentation within ponds, but not ammonia concentrations. Discharges are high in particulate nitrogen at water exchange rates up to 0.3 day^{-1} , but contain mainly dissolved nitrogen at higher rates.

Introduction

Nitrogen components play a key role in aquaculture water quality management, owing to their dual role as nutrients and toxicants. Extensive and semi-intensive aquaculture rely on primary production, which may be enhanced by the deliberate input of nitrogen into the water column through fertilization. In intensive aquaculture, production relies almost entirely on the direct feeding of animals with organic forms of nitrogen, and management aims to reduce the concentration of toxic nitrogen components which are inevitably added to the water by excretion and feed loss. Many intensive aquaculture systems use very high rates of water exchange, or recirculation with water treatment, to maintain dissolved nitrogen components below toxic levels. Other intensive systems operate at relatively low rates of water exchange and rely heavily on biological nitrogen transformation within the production pond to maintain water quality. Such systems make use of the nutrient role of dissolved nitrogen components to limit their concentrations and toxicity.

The capacity of intensive pond ecosystems to transform and remove nitrogen metabolites from the water column has received considerable attention in recent years, as a potential solution to some of the environmental problems associated with intensive aquaculture. Biological nitrogen transformation in intensive ponds has been studied in some detail at a fundamental level (van Rijn, Diab & Shilo 1984). However, the relationship between farming intensity, water management and nitrogen dynamics is still poorly understood, and management implications are often controversial (Boyd 1995; Hopkins, Sandifer & Browdy 1995). In a recent survey (NACA 1997) of intensive shrimp farming in Asian countries, national averages of stocking density (8–114 postlarvae m^{-2}) and daily water exchange (1–19%) were found to vary widely, indicating an even wider variation between individual farms. High levels of water exchange are often adopted by farmers to remedy actual or perceived water quality problems as they arise. By contrast, low water exchange systems of moderate intensity are being promoted to reduce the risk of cross-farm pollution and transfer of pathogens, and to reduce the environmental impact of farms (Hopkins *et al.* 1995; Kongkeo 1997).

The present study uses a mathematical modelling approach to investigate the relationship between farming intensity (measured as stocking density), water management (measured as the daily water exchange rate), and the capacity of the pond ecosystem to maintain acceptable levels of nitrogen metabolites. A mathematical model for nitrogen dynamics in intensive aquaculture ponds is developed, incorporating the transformation and removal processes of excretion and mineralization, assimilation by phytoplankton, nitrification, volatilization and discharge. The model is calibrated independently for two commercial shrimp farms in Thailand and is then cross-validated. The relative importance of different nitrogen removal processes on the two farms is assessed. Model predictions are then used to evaluate the impact of farming intensity and water management on the concentrations of nitrogen metabolites and phytoplankton in the water column, as well as total dissolved and particulate nitrogen discharge.

Materials and methods

Conceptual model

A conceptual model of nitrogen transformations and removal in an intensive aquaculture pond is shown

in Fig. 1. Nitrogen added to the pond in the form of feed is either incorporated into animal tissue, or transformed into ammonia (total ammonia nitrogen, TAN) through excretion by animals or mineralization of lost feed (van Rijn *et al.* 1984). Ammonia may be transformed to nitrate via nitrite (here combined as NO) by bacterial nitrification. Both TAN and NO may be assimilated by phytoplankton (Chl) and thereby transformed into particulate organic nitrogen. All nitrogen components may be discharged, i.e. lost from the water column through water exchange. Particulate nitrogen may also be removed from the water column by sedimentation. Volatilization of ammonia may occur at high pH, when a significant proportion of TAN occurs unionized as ammonium gas.

In general, intensive aquaculture operations raise single cohorts of animals from larvae or small juveniles to marketable size. Inputs of feed and therefore nitrogen metabolites increase drastically over a culture cycle. Hence, under normal farm conditions, the nitrogen system as shown in Fig. 1 is never at equilibrium but changes dynamically as the culture cycle progresses.

The two biological processes of ammonia transformation, assimilation by plankton and nitrification by bacteria, compete for the same pool of TAN. Empirical evidence suggests that assimilation by phytoplankton dominates the transformation of ammonia in ponds, unless the process is limited by high rates of water exchange or the availability of light or of nutrients other than nitrogen (van Rijn *et al.* 1984; Wrigley & Toerinen 1990). Ammonia half-saturation constants of phytoplankton are about an order of magnitude lower than those of nitrifying bacteria (Joergensen & Gromiec 1989), indicating that algae are more efficient than bacteria at utilizing low levels of ammonia.

Mathematical model

A mathematical model of nitrogen dynamics over the course of a culture cycle was developed to reflect the conceptual model as shown in Fig. 1. The model has three state variables representing the main nitrogen components: ionized and unionized ammonia (TAN), combined nitrite and nitrate (NO), and phytoplankton-bound particulate nitrogen expressed in units of chlorophyll (Chl). Transformations between nitrogen components were described at different levels of mathematical detail,

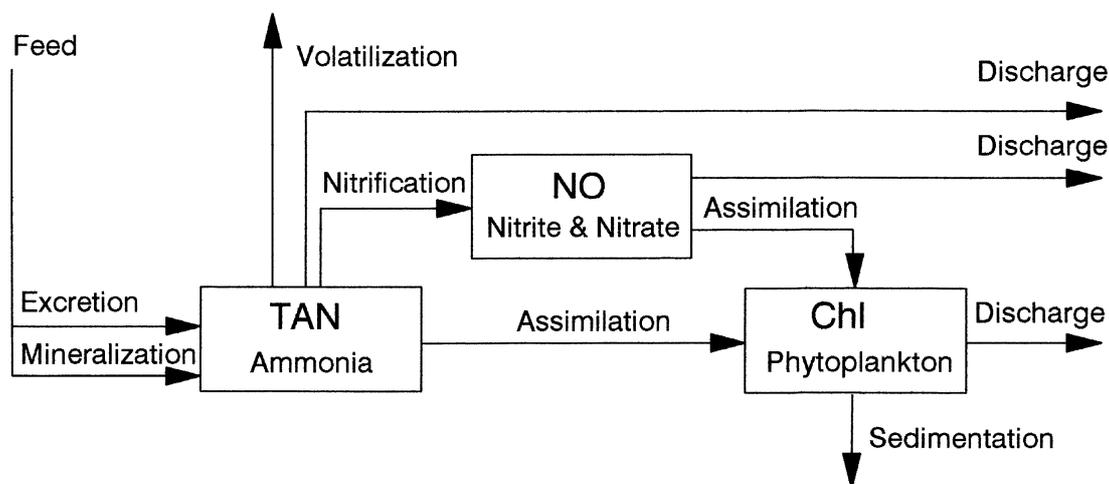


Figure 1 Conceptual model of nitrogen input, transformation and removal processes in intensive aquaculture ponds. Boxes indicate the key nitrogen components represented as state variables in the mathematical model: total ammonia nitrogen (TAN), combined nitrite and nitrate (NO), and particulate organic nitrogen in the form of phytoplankton, i.e. bound to chlorophyll (Chl).

reflecting the importance of each transformation as well as the respective information content of the data used in model calibration.

Nitrogen input was assumed to be exclusively through feed, neglecting the contribution of inflowing water, which has been estimated at about 5% of the total by Briggs & Funge-Smith (1994). Daily feed inputs were assumed to be proportional to the population metabolic rate, as has been shown for fish by Elliott (1975). The amount of feed nitrogen lost to the water column (i.e. not incorporated into shrimp tissue) was assumed to be a constant proportion of the total, and therefore also proportional to the population metabolite rate. The daily population metabolic rate was predicted from the mean weight and density of the animals, respectively described by a von Bertalanffy growth function (VBGF) and an exponential mortality model (e.g. Gulland 1983).

Assimilation by phytoplankton was regarded as a key process in nitrogen dynamics and described at a high level of detail, commensurate also with the data available for calibration. Primary production was described by a standard light- and nutrient-limited model, as used in many other studies (Chapra & Reckhow 1983; Giovannini & Piedrahita 1994). Light limitation was described by Steele's (1962) light inhibition model, integrated over the water column with light conditions defined by the Lambert–Beer law. Nitrogen and phosphorus

limitation were described by Michaelis–Menten models. Phytoplankton was assumed to assimilate both TAN and NO, in proportion to their relative concentrations in the water column (i.e. without a specific preference).

Nitrification, volatilization, sedimentation and discharge of nitrogen were described as first-order rate processes. The full model is given in the mathematical appendix.

Data used for model calibration

The model was calibrated independently for two commercial shrimp farms of different production intensity, located in south-east Thailand (Ranod Province). Both farms cultured *Penaeus monodon* Fabricius in production cycles of approximately 4 months duration. The low-intensity (L) farm used three ponds of 0.62 ha (1 m deep) each, stocked with postlarvae at 43 m⁻², and achieved a production of about 4 t ha⁻¹ cycle⁻¹. The high-intensity (H) farm used four ponds of 0.31 ha (1 m deep) each, stocked at 98 m⁻², and achieved a production of almost 9 t ha⁻¹ cycle⁻¹. Both farms used commercial pelleted feeds. Feeding rates were based on tables supplied by feed manufacturers, with small adjustments made daily in response to actual consumption. Total feed inputs to the two farms differed in proportion to stocking density. Otherwise the management of the

two farms was similar. Both farms followed partial water exchange schedules, exchanging on average 0.4%, 4%, 6% and 8% of pond water per day in the first, second, third and fourth month of the production cycle respectively. From the second month of the cycle onwards, paddlewheels were used for aeration and circulation of the ponds, running for 20 h day⁻¹ at a power of 7.5–10 kW ha⁻¹. Farm H used long-arm paddlewheels and achieved higher rates of circulation in its relatively small ponds than farm L, which used short-arm paddlewheels in larger ponds.

Water quality data were collected weekly from both farms, over a full production cycle in the dry season of 1993. The following water quality parameters relevant to the present study were determined: total ammonia-N (TAN), nitrite-N (NO₂), nitrate-N (NO₃), dissolved reactive phosphorus (DRP), chlorophyll *a* (Chl), Secchi disc depth and pH. The ponds on each farm were treated as replicates, and mean values of water quality parameters were used for model calibration. Total numbers and mean weight of shrimp were determined at stocking and at harvesting. Additional data on the growth pattern in farms similar to those monitored for water quality were used to fit the growth model. The total nitrogen added to the ponds and incorporated into shrimp tissue was determined from total feed input, shrimp yield and proximate analysis of feed and shrimp carcasses.

A more detailed description of the farms and data collection can be found in Briggs & Funge-Smith (1994), who also provide summary statistics and nutrient budgets based on these data.

Model calibration

Two types of model parameters can be distinguished on the basis of their role in the model and the way in which they are estimated. Parameters such as shrimp growth or pond depth describe management or environmental factors which constitute forcing functions in the nitrogen dynamics model. Management/environment parameters were estimated directly from the appropriate data and fixed. Parameters such as the algal growth rate or the nitrification rate describe dynamic processes in the nitrogen model. Nitrogen dynamics parameters were estimated using a simulation approach, identifying sets of parameters that provided a good description of observed water quality dynamics over the production cycle.

Management/environment parameters were estimated as follows. Only stocking and harvesting weights were available for the monitored farms. Hence VBG parameters were determined from fortnightly weight records for farms under similar management and yielding similar harvesting weights. Mortality rates were estimated from the numbers stocked and harvested on the monitored farms. Surface light intensity was set to an average dry season value measured in Bangkok. Extinction rates from Chl and from non-Chl solids were determined by first transforming Secchi disc readings into total extinction coefficients using the relationship of Poole & Atkins (1929). A linear regression of total extinction coefficients against Chl concentration allowed to separate Chl from non-Chl extinction. The allometric scaling of the ammonia input rate was assumed to equal that of the metabolic rate. The ammonia input rate at unit weight of shrimp (*a*) was determined as the value for which cumulative TAN input over the cycle equalled the total feed nitrogen not incorporated into shrimp tissue. The total nitrogen lost was calculated as the difference between total nitrogen input and total nitrogen incorporated into shrimp tissues, as given in Briggs & Funge-Smith (1994).

A simulation approach was used to determine combinations of the eight nitrogen dynamics parameters that provided a satisfactory fit to the observed time series of TAN, NO and Chl concentrations. Initial ranges for the nitrogen dynamics parameters were obtained from the literature, in particular Di Toro, O'Connor, Thomann & Mancini (1975), Stumm & Morgan (1981), Chapra & Reckhow (1983), Joergensen & Gromiec (1989), and Giovannini & Piedrahita (1994). In the simulations, parameter values were scored at random from uniform distributions over the defined ranges. Predictions of TAN, NO and Chl were generated by solving the model for the full production cycle, starting from observed initial values. The goodness of fit for each set of parameters was determined using the sum of squared differences (SSQ) between the observed and expected values of TAN, NO and Chl over the production cycle. A combined SSQ was calculated as the sum of the SSQs for TAN, NO and Chl, weighting each series SSQ by the inverse series SSQ of the best-fitting sets through iterative re-weighting. All parameter sets with a combined SSQ within 10% of the lowest combined SSQ were used for further analysis and prediction. Each scored set of nitrogen dynamics

parameters was evaluated separately for the L and H farms, using the respective management/environment parameters.

Cross-validation of the model

Cross-validation of the model between the two farms was carried out by predicting ammonia concentrations in each farm using the nitrogen dynamics parameter sets estimated from the other farm, together with own-farm management/environment parameters. To assess which management/environment differences between the two farms explained the largest part of the differences in TAN, predictions were obtained for each farm using the other-farm nitrogen dynamics and management/environment parameters, and changing management/environment parameters to own-farm values one at a time.

Relative importance of nitrogen removal processes

The importance of different nitrogen removal processes in the two farms was evaluated by integrating, over the full production cycle, the amounts of nitrogen sedimented or discharged in particulate form (bound to Chl), discharged in dissolved form (as TAN or NO), or volatilized (as unionized ammonia). The final drainage of the pond was assumed to result in the discharge of all particulate and dissolved nitrogen from the water column, but not in the resuspension of sediments. Hence end-of-cycle concentrations of particulate and dissolved nitrogen in the water column were added to the discharge in the respective categories, while the pool of sedimented nitrogen was not affected by drainage.

Impact of stocking density on TAN and Chl

Predictions of TAN and Chl concentrations at the end of the production cycle were generated for a range of stocking densities, using the identified L and H farm parameter sets. To evaluate the effect of turbidity on the TAN and Chl response to stocking density, predictions for the H farm sets were also generated using the L farm non-Chl extinction coefficient. Predictions were generated for all identified sets of nitrogen dynamics parameters, so as to assess the uncertainty of predictions.

Impact of water management on TAN and Chl

Predictions of the effect of different water exchange rates on ammonia and chlorophyll concentrations were generated for both farms. The relative pattern of increasing water exchange over the production cycle was maintained, and all exchange rates varied by the same factor.

To explore the combined impact of stocking density and water exchange on the concentrations of nitrogen components in the water column, predictions for the full stocking density–water exchange plane were generated from the best-fitting parameter set for the L farm.

Impact of water management on nitrogen discharge

To explore the impact of water management on nitrogen discharge, the predicted amounts of nitrogen discharged in particulate form (bound to Chl) and in dissolved form (as TAN or NO) were integrated over the full production cycle. Predictions of the total dissolved and particulate discharges were generated for the full stocking density–water exchange plane, using the best-fitting parameter set for the L farm.

Results

Model calibration

Table 1 enlists the estimated values of management/environment parameters, and the initial ranges and the ranges of the best-fitting sets of nitrogen dynamics parameters. Most of the management/environment parameters estimated for the L and H farms are equal. Exceptions are the stocking density, mortality rate, non-chlorophyll extinction coefficient, and DRP concentrations.

Initial ranges for the nitrogen dynamics parameters were set to cover values found in other modelling studies, or measured directly. The TAN volatilization rate in aerated ponds has not been measured or modelled before, and its possible range was therefore difficult to determine. The application of two-layer diffusion theory with diffusion coefficients for natural lakes (Stumm & Morgan 1981; Chapra & Reckhow 1983) suggests ammonium volatilization rates of about 0.2 day^{-1} in lakes of 1 m depth. Aeration at the power used

Table 1 Model parameter values identified in the calibration process for the low-intensity (L) and high-intensity (H) farm. Management/environment parameters were estimated prior to simulation from farm records, water quality data and secondary information. Nitrogen dynamics parameters were identified by simulation. The table gives the initial ranges from which parameter sets were scored, and the ranges of the best-fitting sets. See mathematical appendix for further details

Parameter	Initial range	Farm L estimated	Farm H estimated
Management/environment parameters			
Shrimp VBGF K (day^{-1})	Fixed	0.0055	0.0055
Shrimp VBGF W_z (g)	Fixed	185	185
Shrimp VBGF W_0 (g)	Fixed	0.01	0.01
Shrimp stocking density N_0 (l^{-1})	Fixed	0.043	0.098
Shrimp mortality rate M (day^{-1})	Fixed	0.006	0.007
TAN input rate a ($\text{mg g}^{-1} \text{day}^{-1}$)	Fixed	3.2	3.2
Allometric scaling of TAN input b	Fixed	0.75	0.75
Pond depth z (m)	Fixed	1.0	1.0
Surface light intensity I_0 ($\text{E m}^{-2} \text{day}^{-1}$)	Fixed	40	40
Extinction from non-Chl k_{other} (m^{-1})	Fixed	2.6	4.0
Extinction from Chl k_{Chl} ($\text{m}^{-1} \text{mg}^{-1}$)	Fixed	11.9	11.9
Water exchange rate f (day^{-1})			
Month 1	Fixed	0.004	0.004
Month 2	Fixed	0.035	0.035
Month 3	Fixed	0.059	0.059
Month 4	Fixed	0.077	0.077
Average DRP concentration (mg l^{-1})			
Month 1	Fixed	0.005	0.011
Month 2	Fixed	0.024	0.028
Month 3	Fixed	0.004	0.022
Month 4	Fixed	0.011	0.012
Nitrogen dynamics parameters			
Sedimentation rate s (day^{-1})	0.0–1.0	0.11–0.65	0.45–0.83
Phytoplankton growth rate g_{max} (day^{-1})	0.5–3.0	0.6–2.1	1.4–2.3
Saturation light intensity I_{sat} ($\text{E m}^{-2} \text{day}^{-1}$)	10–80	29–79	22–68
Nitrogen half-saturation K_{SN} (mg l^{-1})	0.0–0.1	0.06–0.1	0.008–0.031
Phosphorus half-saturation K_{SP} (mg l^{-1})	0.0–0.1	0.00001–0.00042	0.00001–0.00015
Nitrogen-to-Chl ratio c	3–27	5–22	7–12
Nitrification rate n (day^{-1})	0.0–0.2	0.06–0.2	0.013–0.027
Volatilization rate v (day^{-1})	0.0–0.2	0.007–0.2	0.15–0.2

in the monitored shrimp farms increases transfer rates of oxygen (which are limited primarily by liquid phase diffusion) to about five times the natural value (Chapra & Reckbow 1983; Lawson 1994). Assuming that aerators have a similar effect on ammonium transfer (which is limited primarily by gas phase diffusion), ammonium volatilization rates of 1 day^{-1} are possible. At the average pH of 8.5 found in the monitored shrimp ponds, about 20% of total ammonia is un-ionized and may be volatilized. Therefore, the maximum volatilization rate for total ammonia (TAN) in the monitored shrimp ponds was set at 0.2 per day.

A total of 2 million parameter sets were scored and evaluated, of which 25 sets were within 10%

of the best SSQ for the L farm, and 7 sets were identified by the same criterion for the H farm. There was no overlap between the sets identified for each farm, i.e. none of the sets provided an equally good fit for both farms. For many parameters, the identified sets span a wide range, sometimes the full initial range. Ranges identified for the H farm are often more narrow than those identified for the L farm. Only one parameter, the phosphorus half-saturation constant K_{SP} , has consistently been estimated within a narrow range of very low values.

Predicted total ammonia (TAN) input into the water column of the L farm over a full production cycle is shown in Fig. 2. Predictions are based on the estimated parameters (Table 1) of the growth,

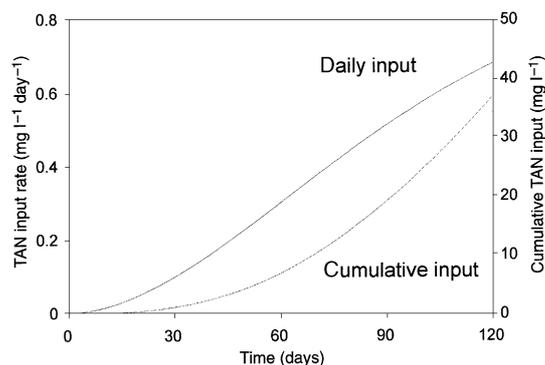


Figure 2 Daily and cumulative input of total ammonia nitrogen (TAN) over the course of a production cycle, for the low-intensity L farm stocking density of 43 m⁻². The cumulative input equals the ammonia concentration that would be reached in the water column if no ammonia transformation or removal occurred during the cycle.

mortality and TAN input models. Daily input of TAN rises throughout the cycle, to more than 0.6 mg l⁻¹ day⁻¹ at the time of harvesting. Also shown is the cumulative TAN input, rising drastically in the second half of the cycle to reach 38 mg l⁻¹ at the time of harvesting.

The observed and predicted patterns of TAN, NO and Chl concentrations during the production cycle in both farms are shown in Fig. 3. Observations are shown as solid squares, and each line represents predictions based on one of the identified parameter sets. Observed and predicted values of TAN are much lower in the L farm than in the H farm. The same holds for NO, but in both farms the concentrations of NO are very low, rarely exceeding 10% of the concurrent TAN concentration. Chl reaches slightly higher values in the L than in the H farm.

Cross-validation of the model

Cross-validation results for the average and range of TAN during the final month of the production cycle are given in Table 2. The L farm TAN range predicted using H farm nitrogen dynamics parameter sets is lower than both the observed values, and the values predicted using L farm parameter sets. The H farm TAN range predicted using L farm nitrogen dynamics parameter sets is very wide and covers both the observed values, and the values predicted using H farm nitrogen dynamics parameters.

Predictions of L farm TAN using the full H farm parameters except for L farm mortality, non-Chl

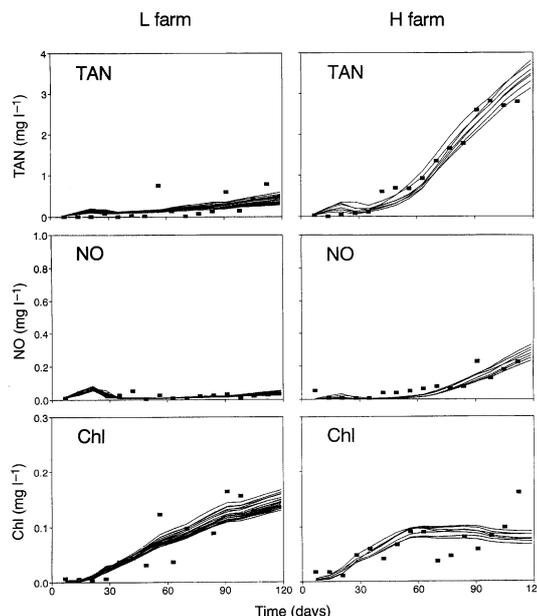


Figure 3 Model predictions (lines) and observed values (solid squares) of total ammonia nitrogen (TAN), nitrite/nitrate (NO) and chlorophyll (Chl) over the course of production cycles in the low-intensity L and high-intensity H farms. Each line represents predictions from one of the identified parameter sets.

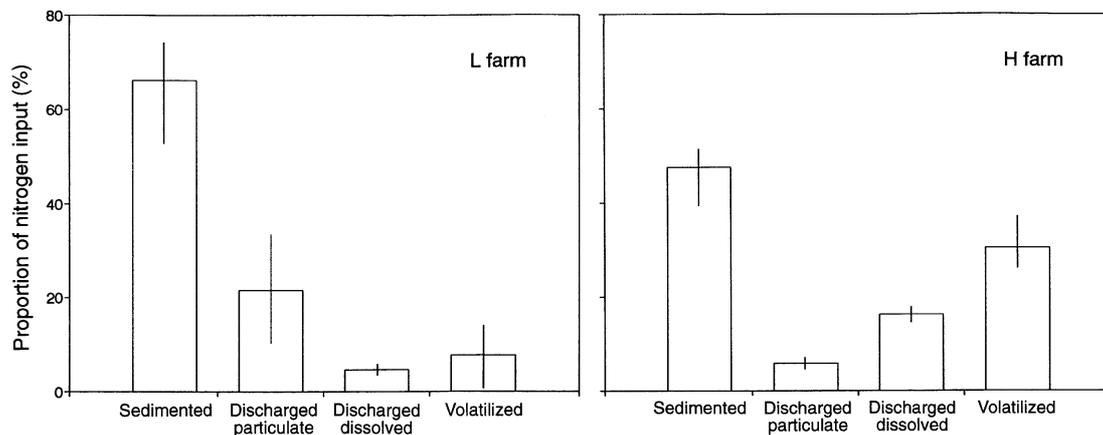
extinction or stocking density show that stocking density has the greatest effect on TAN, followed by non-Chl extinction and mortality. Results of the same procedure for H farm TAN show the same pattern. In both cases, a change of stocking density alone is sufficient to obtain predictions of TAN concentrations in the other farm that correspond well to the observed values.

Relative importance of nitrogen removal processes

Model predictions of the fate of the total nitrogen added to the water column in the course of a production cycle are shown in Fig. 4. The mean and range of predictions obtained from the different parameter sets are indicated. The relative importance of different processes that remove nitrogen from the water column differs between the L and H farms. Sedimentation of particulate nitrogen (phytoplankton) always accounts for the largest proportion of removal, 66% in the L and 48% in the H farm. In the L farm, the second most important removal process is discharge of particulate nitrogen (21%),

Table 2 Cross-validation of model predictions between the L and H farms. The observed and predicted mean and range (in brackets) of average TAN in the last month of the production cycle are given

Prediction method	TAN (mg l ⁻¹)	
	L farm	H farm
Observed	0.49 (0.14–0.79)	2.72 (2.59–2.81)
Predicted by own-farm parameters	0.21 (0.13–0.39)	2.84 (2.55–3.36)
Predicted by other-farm nitrogen dynamics and own-farm management/environment parameters	0.04 (0.02–0.08)	3.26 (1.23–5.65)
Predicted by all other-farm parameters, except for own-farm:		
mortality	3.55 (3.25–4.02)	0.18 (0.12–0.31)
non-Chl extinction	0.40 (0.13–1.06)	0.64 (0.26–1.43)
stocking density	0.20 (0.09–0.31)	2.10 (1.23–5.65)

**Figure 4** Fate of the total nitrogen added to the water column as ammonia in the course of a production cycle, as predicted by the model for the low-intensity L and high-intensity H farms. Bars indicate averages, and lines indicate ranges of predictions obtained from the identified parameter sets.

while dissolved discharge (5%) and volatilization (8%) play only a minor role. By contrast, volatilization (30%) and dissolved discharge (16%) are important removal processes in the high-intensity pond, while particulate discharge (6%) is relatively unimportant.

Impact of stocking density on TAN and Chl

The effect of stocking density on end-of-cycle concentrations of ammonia and chlorophyll is shown in Fig. 5, for both the L and H farm parameter sets. For the L farm parameter sets, TAN concentra-

tions are very low and almost independent of stocking density up to about 60 per m², but become linearly dependent on stocking density thereafter. The corresponding Chl concentrations rise linearly with stocking density at first, but are virtually constant for densities above 60 per m². The H farm parameter sets yield qualitatively similar patterns, but the linear rise of TAN and constant level of Chl begin at lower stocking densities of about 30 per m². When the H farm parameter sets are used in conjunction with the L farm non-chlorophyll extinction coefficient, the predicted effects of stocking density on TAN and Chl are very similar to the predictions using L farm sets.

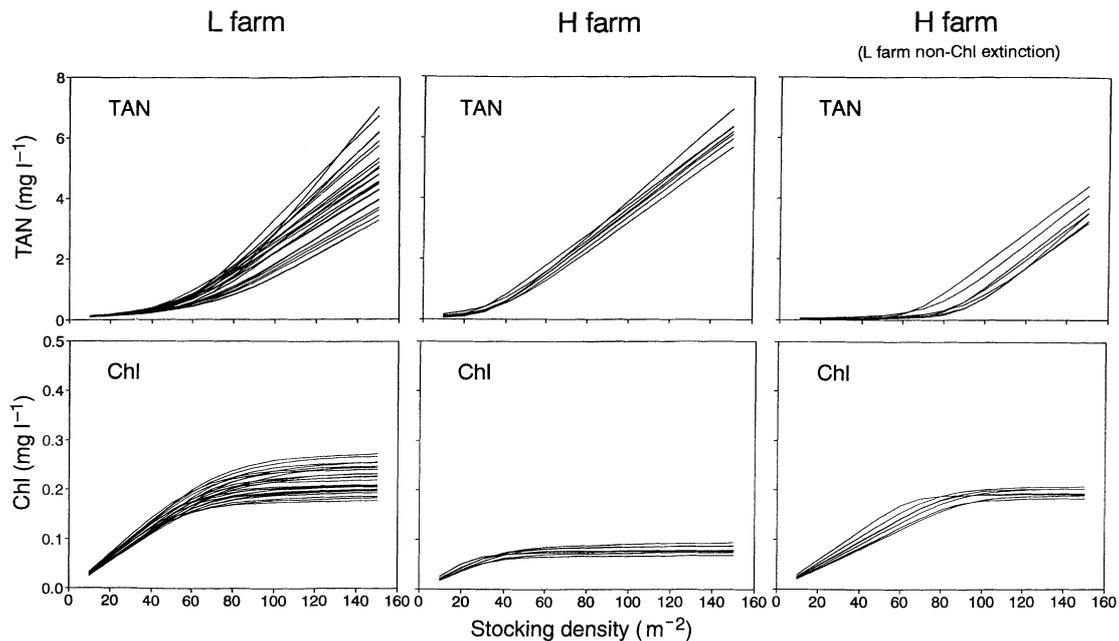


Figure 5 Impact of stocking density on total ammonia (TAN) and chlorophyll (Chl) concentrations at the end of the production cycle, predicted using the best-fitting parameter sets for the low-intensity L and high-intensity H farms. H farm predictions are also given for the L farm value of the non-Chl extinction coefficient.

Impact of water management on TAN, NO and Chl

The predicted impact of different water exchange rates on TAN and Chl at the end of the production cycle is shown in Fig. 6. In the L farm, TAN concentrations are lowest if no water is exchanged, reach a maximum at exchange rates between 0.2 and 0.4 day⁻¹, and decline again at very high exchange rates above 0.4 day⁻¹. The corresponding Chl concentrations decline sharply with increasing water exchange, and are virtually nil at exchange rates above 0.4 day⁻¹. In the H farm, water exchange rates below 0.2 day⁻¹ have little impact on TAN concentrations. Some parameter sets predict a continuous, slight decline of TAN with increasing exchange, while others predict a slight increase up to exchange rates of 0.1 day⁻¹, followed by a decline. Only exchange rates above 0.2 day⁻¹ result in substantial reductions of TAN. The corresponding Chl concentrations decline continuously with increasing water exchange and are virtually nil at rates above 0.3 day⁻¹.

The combined impact of stocking density and water exchange on TAN, NO and Chl concentrations at the end of the production cycle is shown in Fig. 7.

TAN concentrations always increase with stocking density, regardless of the water exchange rate. The impact of water exchange on TAN is dependent on stocking density. At moderate densities up to about 90 m⁻², TAN reaches a maximum at intermediate water exchange rates of 0.2–0.4 day⁻¹. At higher densities, TAN declines continuously with increasing water exchange. The overall pattern for NO is similar to that for TAN, but the effects of both stocking density and water exchange are more pronounced. Very high NO concentrations occur when high stocking densities are combined with low water exchange. Chl concentrations increase with stocking density up to about 60 m⁻² but remain constant at high densities, and always decline with increasing water exchange.

Impact of water management on nitrogen discharge

The combined impact of stocking density and water exchange on the total discharge of dissolved and particulate nitrogen over a production cycle is shown in Fig. 8. Particulate discharges show a clear maximum at water exchange rates between 0.1 and

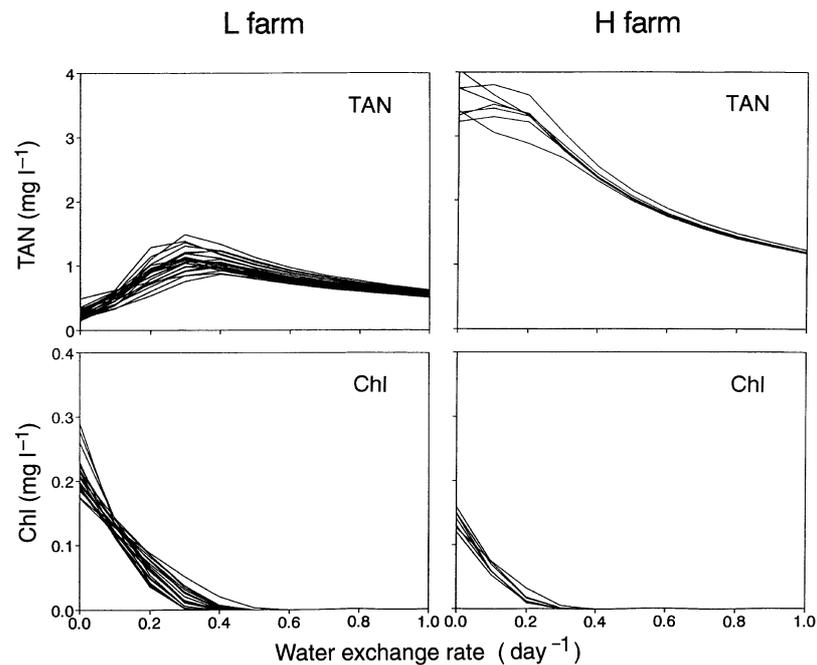


Figure 6 Impact of the water exchange rate on total ammonia (TAN) and chlorophyll (Chl) concentrations at the end of the production cycle, for the low-intensity L and high-intensity H farms. Daily water exchange rates refer to the final month of the cycle.

0.3 day⁻¹. Dissolved discharges increase continuously with both water exchange rate and stocking density.

Discussion

Model calibration

In the calibration procedure, for each farm a number of parameter sets have been identified that fit the water quality data about equally well. While only particular combinations of the parameters describe the data well, individual parameters often assume widely different values in different sets. The parameter estimates are correlated, because the information content of the water quality data is not sufficient to separate the effects of individual parameters on nitrogen dynamics. However, each identified set is consistent with the available information and may be used for predictions of nitrogen dynamics under different management scenarios. Taken together, predictions obtained from the different parameter sets for the same management scenario provide an indication of the uncertainty surrounding these predictions.

The simulation method was used to calibrate the model, because a large number of parameters had to be estimated from a limited and heterogeneous set of data. The procedure allows for the possibility that several different sets of parameters fit the available data about equally well, but give different predictions for situations for which no data are available. Related calibration procedures have previously been used to identify parameter sets for lake water quality models (van Straten 1986). Most previous studies involving complex aquaculture water quality models have used eye fitting, i.e. variation of parameters until a 'satisfactory' fit is obtained (e.g. Piedrahita 1990). Numerical search routines that find a best-fitting set of parameters using criteria such as the minimum sum of squares are more objective than eye fitting, but are difficult to use when a large number of parameters need to be estimated from a limited set of data.

Parameter estimates may be improved and prediction uncertainty reduced by experimentally subjecting shrimp ponds to management regimes for which prediction uncertainty is large. The model can thus aid experimental design by identifying experiments that are most likely to resolve

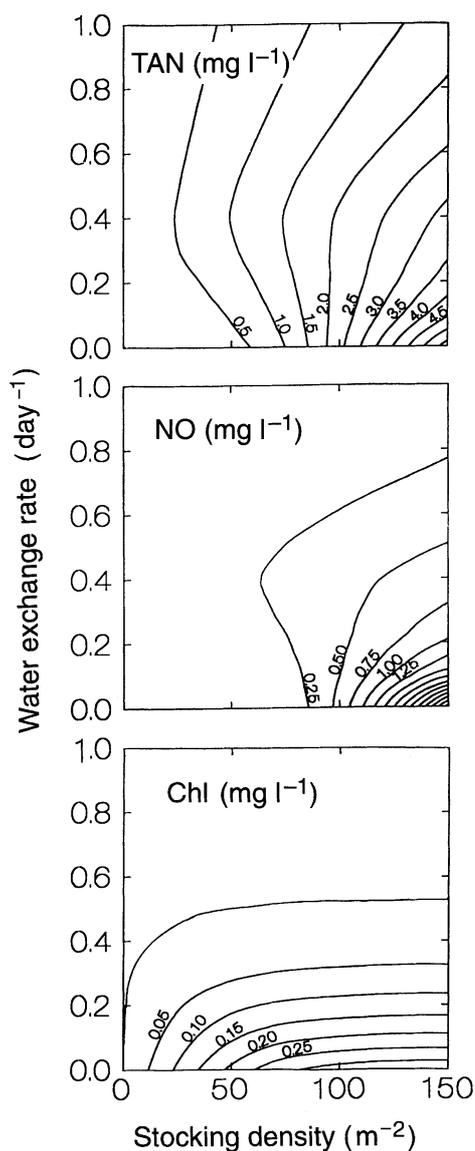


Figure 7 Predicted concentrations of total ammonia (TAN), nitrite/nitrate (NO) and chlorophyll (Chl) at the end of the production cycle, as a function of stocking density and daily water exchange during the final month. Predictions from the best-fitting set of parameters for the low-intensity L farm.

uncertainties, i.e. generate significant results. The calibration procedure could be developed further using a Bayesian approach (Gelman, Carlin, Stern & Rubin 1995), which provides a systematic way of using new information to improve parameter estimates and predictions. The Bayesian approach requires explicit consideration of parameter

probability distributions, and can provide true confidence limits for predictions. A systematic and coordinated process of experimentation and modelling may be an efficient route to the improvement of water quality management in intensive pond culture.

Cross-validation of the model

Cross-validation results indicate that some caution is needed in extrapolating quantitative predictions to farms for which the model has not been calibrated: L farm nitrogen dynamics parameters provide good predictions of H farm TAN (albeit with a large uncertainty), but H farm parameters underestimate L farm TAN. However, predictions obtained from L and H farm nitrogen dynamics parameters for the same set of management/environment parameters are very consistent in qualitative terms, and quantitative differences are moderate. This is also evident in Fig. 5, and in comparing Figs 6 and 7.

Of the management/environment parameters that differ between the L and H farms, stocking density clearly has the greatest impact on TAN concentrations, but the impact of non-chlorophyll extinction is also significant.

Relative importance of nitrogen removal processes

The relative importance of different nitrogen removal processes differs between the L and H farms. In the L farm, almost all dissolved nitrogen (87%) is assimilated by phytoplankton and is either sedimented or discharged in particulate form. In the H farm, TAN inputs exceed the capacity of phytoplankton for assimilation, which accounts for only 54% of the total nitrogen removal. High concentrations of dissolved nitrogen (TAN and NO) develop in the water column, and volatilization and discharge of dissolved nitrogen become important removal processes. The relative importance of different nitrogen removal processes is clearly dependent on farming intensity.

Impact of stocking density on TAN and Chl

Over a wide range of low-to-moderate stocking densities, phytoplankton production increases with density and removes virtually all ammonia from

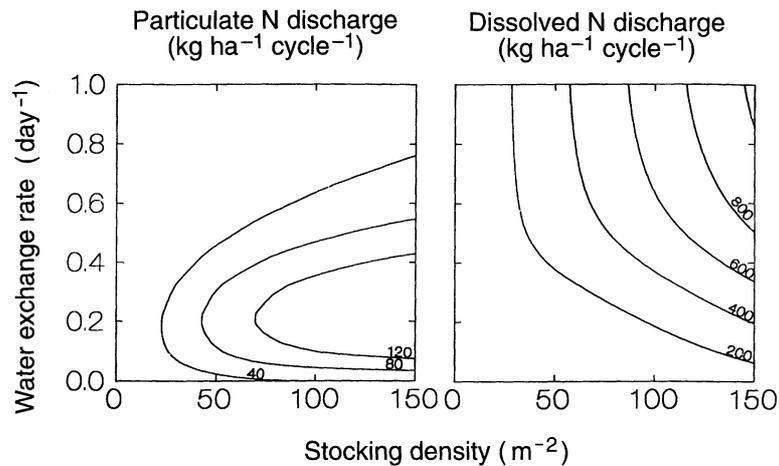


Figure 8 Predicted total particulate and dissolved nitrogen discharged in the course of a production cycle, as a function of stocking density and daily water exchange in the final month. Predictions from the best-fitting set of parameters for the low-intensity L farm.

the water. However, primary production is fundamentally limited by light, and possibly the availability of nutrients other than nitrogen. This defines a threshold stocking density or carrying capacity above which TAN inputs exceed the phytoplankton assimilation capacity, and excess dissolved nitrogen remains in the water column. The carrying capacity is dependent on the level of non-Chl extinction (turbidity). Estimated carrying capacities for the ponds used to calibrate the model are about 60 m⁻² (equivalent to a production of 6 t ha⁻¹ cycle⁻¹) at a non-Chl extinction of $k_{\text{other}} = 2.6 \text{ m}^{-1}$, and 30 m⁻² (equivalent to 3 t ha⁻¹ cycle⁻¹) at $k_{\text{other}} = 4.0 \text{ m}^{-1}$. The H farm thus combines high stocking density with low carrying capacity (due to high non-Chl extinction), which results in very high TAN concentrations in the water column. To achieve a high carrying capacity, non-Chl turbidity should be limited. Non-Chl turbidity in intensive ponds is often caused by solids eroded from pond banks through the action of aerators. Hence non-Chl turbidity could be reduced by adopting aeration methods that result in lower circulation rates at the pond periphery, or by the use of pond liners.

Impact of water management on TAN, NO and Chl

Model predictions indicate a complex relationship between water management, farming intensity and the concentration of nitrogen components (Fig. 7).

At low to moderate intensity, where phytoplankton assimilation is sufficient to maintain acceptable concentrations of dissolved nitrogen, water exchange up to about 0.4 day⁻¹ is predicted to increase rather than reduce dissolved nitrogen concentrations. At higher intensities, where TAN inputs exceed the phytoplankton assimilation capacity, water exchange at any rate is predicted to reduce dissolved nitrogen levels. In order to limit the concentrations of potentially toxic dissolved nitrogen components (TAN and nitrite-NO), fundamentally different water management strategies are indicated for farms of different intensity. At low to moderate farming intensity, water exchange should be minimized so as to maximize phytoplankton production and achieve the lowest possible concentrations of TAN and NO. At high farming intensity, water exchange is the only option to reduce TAN and NO levels, but very high rates of exchange are required to achieve substantial effects.

In a recent survey (NACA 1997), average daily water exchange in Asian shrimp farms was found to range from 1% to 19%, equivalent to instantaneous rates of 0.01 to 0.21 day⁻¹. Model results suggest that water exchange at these rates has a strong impact on Chl concentrations, but does not reduce TAN or NO levels, except at very high intensities (stocking density over 90 m⁻², production over 9 t ha⁻¹ cycle⁻¹). Results therefore support Boyd's (1995) assertion that routine water exchange as

practised in brackish water aquaculture is inefficient, at least with respect to dissolved nitrogen levels. However, water exchange may be beneficial as an emergency measure in specific situations, such as phytoplankton die-offs.

Impact of water management on nitrogen discharge

Water management has a strong impact on the total amount and the form of nitrogen discharge. Total discharge rises continuously with increasing water exchange (Fig. 8). At exchange rates below 0.3 day^{-1} , discharge from low-intensity farms consists largely of particulate nitrogen, while discharge from high-intensity farms contains a mixture of particulate and dissolved nitrogen components. At higher rates of water exchange, dissolved nitrogen components predominate in the discharge regardless of farming intensity.

The quantity and form of nitrogen discharged from production ponds has important implications for the design of water treatment facilities for flow-through or recirculation systems. Two types of biological water treatment systems are promoted for intensive shrimp farms (Hopkins *et al.* 1995): filter-feeding organisms to remove particulate forms of nitrogen, and macroalgae to assimilate dissolved forms of nitrogen. Systems removing particulate nitrogen are likely to be most effective when discharges of this form are highest, i.e. at water exchange rates between 0.1 and 0.3 day^{-1} . By the same argument, systems removing dissolved nitrogen are likely to be most effective at higher rates of water exchange. At the water exchange rates currently practised in intensive shrimp farms (see previous section), treatment systems for low-intensity farms must be designed to remove particulate nitrogen, while treatment systems for high-intensity farms must remove both particulate and dissolved nitrogen.

Conclusions

1 Assimilation by phytoplankton (with subsequent sedimentation or discharge) is the principal process of TAN removal from the water column of intensive shrimp ponds. Nitrification and volatilization become important only when TAN inputs exceed the phytoplankton assimilation capacity, i.e. the carrying capacity of the pond.

2 The carrying capacity of a pond for TAN removal is negatively affected by non-Chl turbidity, which should therefore be maintained at low levels. The carrying capacity of the intensive shrimp ponds used for model calibration was estimated at $60 \text{ postlarvae m}^{-2}$ (equivalent to a production of $6 \text{ t ha}^{-1} \text{ cycle}^{-1}$) at a non-Chl extinction of 2.6 m^{-1} .

3 In ponds managed within their carrying capacity, the lowest TAN and NO levels are achieved at no or very low water exchange, while the highest levels occur at exchange rates between 0.2 and 0.4 day^{-1} . In ponds managed significantly above their carrying capacity, TAN and NO concentrations are highest at no water exchange and decline continuously with increasing exchange.

4 Water exchange rates in the range currently practised in Asian intensive shrimp farms ($0.01\text{--}0.2 \text{ day}^{-1}$) are ineffective in limiting TAN and NO concentrations, but reduce phytoplankton abundance and sedimentation within ponds.

5 Total nitrogen discharges increase with water exchange. Exchange rates up to 0.3 day^{-1} result in discharges high in particulate nitrogen, with an increasing contribution from dissolved nitrogen at high farming intensities. Exchange rates higher than 0.3 day^{-1} result in discharges primarily of dissolved nitrogen. At the exchange rates currently practised in intensive shrimp farms, effluent treatment must remove primarily particulate nitrogen (e.g. by filter-feeding organisms), but also dissolved nitrogen (e.g. by macroalgae) where farming intensity exceeds the pond carrying capacity.

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Mathematical appendix

Nitrogen dynamics model

The nitrogen dynamics model is given by the following set of coupled differential equations for the three state variables:

$$\frac{dC_{\text{TAN}}}{dt} = A - (n + v + f) C_{\text{TAN}} - g c C_{\text{Chl}} \frac{C_{\text{TAN}}}{C_{\text{TAN}} + C_{\text{NO}}}, \quad (1)$$

$$\frac{dC_{\text{NO}}}{dt} = n C_{\text{TAN}} - f C_{\text{NO}} - g c C_{\text{Chl}} \frac{C_{\text{NO}}}{C_{\text{TAN}} + C_{\text{NO}}}, \quad (2)$$

$$\frac{dC_{\text{Chl}}}{dt} = g C_{\text{Chl}} - (s + f) C_{\text{Chl}}, \quad (3)$$

where: A is total ammonia input per unit time ($\text{mg l}^{-1} \text{day}^{-1}$); C_{TAN} represents the concentration of total ammonia nitrogen (mg l^{-1}); C_{NO} denotes the concentration of nitrate and nitrite nitrogen (mg l^{-1}); C_{Chl} is the concentration of chlorophyll a (mg l^{-1}); c represents the nitrogen-to-chlorophyll ratio of algae; f is the water exchange rate (day^{-1}); g is the growth rate of algae (day^{-1}); n denotes the nitrification rate (day^{-1}); s represents the sedimentation rate of algae (day^{-1}); t is time (days); and v denotes the volatilization rate of ammonia (day^{-1}).

Individual process models

Ammonia input is proportional to the population metabolic rate:

$$A = a N W^b, \quad (4)$$

where: a represents ammonia input per unit weight, at unit body weight ($\text{mg g}^{-1} \text{day}^{-1}$); b is the allometric scaling factor of the metabolic rate; N is

the population density of farmed animals (l^{-1}); and W denotes body weight of farmed animals (g).

This formulation assumes that the animals are farmed in single cohorts, i.e. all animals in the pond are of similar age and size. The body weight W_t of animals at time t after stocking is described by a von Bertalanffy growth function (VBGF):

$$W_t = [W_\infty^{1/3} - (W_\infty^{1/3} - W_0^{1/3}) \exp(-K t)]^3 \quad (5)$$

where: K is the growth rate parameter (day^{-1}); W_0 denotes body weight at time of stocking (g); and W_∞ represents asymptotic body weight (g).

The density N_t of shrimp at time t after stocking is given by an exponential mortality model:

$$N_t = N_0 \exp(-M t) \quad (6)$$

where: M denotes the mortality rate (day^{-1}); and N_0 is the stocking density (l^{-1}).

The growth rate g of photoplankton is defined as:

$$g = g_{\max} L_{\text{light}} L_N L_P \quad (7)$$

where: g_{\max} is the maximum growth rate in the absence of limitation (day^{-1}); L_{light} is the light limitation coefficient; L_N is the nitrogen limitation coefficient; and L_P is the phosphorus limitation coefficient.

The light limitation coefficient is given by the integral of Steele's light inhibition model over the water column, with light conditions defined by the Lambert–Beer law:

$$L_{\text{light}} = \frac{e}{k} \left\{ \exp \left[- \frac{I_0}{I_{\text{sat}}} \exp(-k z) \right] - \exp \left(- \frac{I_0}{I_{\text{sat}}} \right) \right\} \quad (8)$$

where: e is the base of the natural logarithm; I_0 represents incident light at the surface of the pond ($\text{E m}^{-2} \text{day}^{-1}$); I_{sat} denotes the saturation light intensity for algal growth ($\text{E m}^{-2} \text{day}^{-1}$); k is the extinction coefficient (m^{-1}); and z is pond depth (m).

The extinction coefficient k is the sum of extinction due to chlorophyll a and extinction due to other sources:

$$k = k_{\text{chl}} C_{\text{chl}} + k_{\text{other}} \quad (9)$$

where: k_{chl} represents the extinction per unit concentration of chlorophyll ($\text{m}^{-1} \text{mg}^{-1}$); and k_{other} denotes extinction due to non-chlorophyll sources (m^{-1}).

Nitrogen (ammonia and nitrate) and phosphorus (dissolved reactive phosphorus, DRP) limitation are defined by Michaelis–Menten models:

$$L_N = \frac{C_{\text{TAN}} + C_{\text{NO}}}{(C_{\text{TAN}} + C_{\text{NO}}) + K_{\text{SN}}} \quad (10)$$

$$L_P = \frac{C_{\text{DRP}}}{C_{\text{DRP}} + K_{\text{SP}}} \quad (11)$$

where: C_{DRP} represents the concentration of dissolved reacted phosphorus (mg l^{-1}); K_{SN} is the half-saturation constant of nitrogen (mg l^{-1}); and K_{SP} is the half-saturation constant of phosphorus (mg l^{-1}).