Aquaculture Pond Modeling for the Analysis of Environmental Impacts and Integration with Agriculture: Relationship Between Carbon Input and Sediment Quality in Aquaculture Ponds

Eighth Work Plan, Aquaculture Systems Modeling Research 1A (ASMR1A)

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Introduction

The development of a model to simulate organic matter and nitrogen dynamics in integrated aquaculture-agriculture systems has focused on the modification of an existing aquaculture pond ecosystem model. The following modifications (Jamu and Piedrahita, 1995; Jamu and Piedrahita, 1996) have so far been incorporated into the model:

1. explicit consideration of organic matter and nitrogen transformations;
2. the modification of the fish growth model to include the effects of low quality feed;
3. inclusion of sediments in the mass balance calculations; and
4. the coupling of an agriculture component (terrestrial crop-plant and soil-nitrogen/organic matter) to the aquaculture pond ecosystem model.

The objective of these modifications has been to allow the use of an existing aquaculture pond model to analyze the function of integrated aquaculture-agriculture and the impacts of aquaculture on its surrounding environment. The structure of the model developed allows the simulation of organic matter dynamics and the subsequent release of inorganic nutrients in the water column and sediment.

Agriculture Component Sub Model: Terrestrial Crop, Soil-Nitrogen and Water Balance

The SUCROS model of van Keulen et al. (1982) has been used to simulate crop growth and nitrogen uptake in the crop subsystem. The SUCROS model uses a source-sink approach; gross carbon assimilated feeds a pool of carbohydrates, and the carbohydrates are partitioned into roots, shoots, and storage organs as a function of phenological age of the plant. The modeling of soil nitrogen availability and uptake follows the approach of van Keulen (1982). The nutrients in organic matter are available through decomposition of organic material based on first order kinetics, influenced by moisture, temperature, and the soil's carbon to nitrogen (C/N) ratio. The soil organic matter is divided into three pools based on the reactivity of each pool (Thornley and Verberne, 1989). This approach is similar to that adopted for the aquaculture pond/organic matter dynamics model (Jamu and Piedrahita, 1996). The immobilization of nitrogen is controlled by a switch function that makes N unavailable when the soil C/N ratio is above the microbial C/N ratio. It is assumed that soil moisture is optimal throughout the growing season such that nitrogen is available to the plant through mass flow with the transpiration stream (van Keulen, 1982). The assumption of optimal availability of nitrogen is based on the premise that aquaculture pond water is used to irrigate the crop to maintain optimal soil moisture conditions for the crop under consideration. A feedback loop represented by a linear reduction factor for crop growth as a result of N shortage will be used to reflect changes in soil N content.

Water balance is simulated using simplified calculations for a homogeneous soil layer as affected by transpiration rates, soil type, and soil water content at field capacity (Addiscott and Whitmore, 1987). The leaching of nitrogen from the agriculture component through downward transport of water outside the rooting zone is calculated as the difference between actual soil water content and water content at field capacity for the soil type.

Water Column Organic Matter Decomposition: Effect of Organic Matter C/N Ratio

The multi-pool model of Westrich and Berner (1984) is used to simulate organic matter decomposition both in the water column and the sediment. The implementation of the multi-pool model has been described previously (Jamu and Piedrahita, 1996). The rate of decomposition of organic matter is influenced by water temperature and the C/N ratio. A simple method of incorporating the C/N ratio in the water column is to assume that the C/N ratio of the water column organic matter is constant over time and similar to the C/N ratio of the inputs to the water column. This approach does not require additional equations for updating the C/N ratio to account for the fluctuations in the organic matter nitrogen concentrations. However, preliminary runs of the model have shown that assuming a constant C/N ratio overestimates the decomposition rate of the organic matter. This results in the overestimation of water column nitrogen mineralization and accumulation rates. The C/N ratio in the water column and sediment can be updated at each time step by accounting for the changes in organic matter nitrogen concentrations, which arise due to mineralization and uptake losses. Therefore, modifications that allow the C/N ratio of the water column organic matter to be dependent on the existing organic matter nitrogen concentration were incorporated in the model.

Water Column Organic Matter: Effect of Non-Algal Turbidity on Chlorophyll *a* Production Estimates

The integration of aquaculture and agriculture results in the use of agricultural wastes (e.g. crop wastes in terrestrial crop integration or animal manure in livestock integration). In the PD/A CRSP experiments animal manures and terrestrial crops/plants have been used as pond inputs. The use of animal manures and terrestrial crops/plants and the presence of inorganic materials (e.g., clay) can affect the concentration of non-algal material and the Secchi disk visibility values (SDV) (Bannister, 1974; Carlson, 1977; Burford, 1997).

The existing relationships for calculating a light extinction coefficient for the water column as a function of chlorophyll *a* concentration can only be used when phytoplankton is the major source of turbidity (e.g., Almazan and Boyd, 1979). Nath (1996) modified the Almazan and Boyd relationship by making SDV the independent variable and including a term for non-algal turbidity as follows:

$$SDV = \frac{\alpha}{(Chla + T)^{\beta}} \qquad (1)$$

where

SDV	=	Secchi disk visibility (m);
$Chla$	=	chlorophyll *a* concentration (mg m^{-3});
T	=	non-algal turbidity (mg m^{-3} $Chla$ equivalents);
α and β	=	non-linear regression coefficients.

The SDV estimates are then used to calculate the light extinction coefficient using the Poole and Atkins equation, where the total light extinction coefficient, k_t (m^{-1}) = 1.7/SDV (Poole and Atkins, 1929). The use of Equation (1) is limited to conditions for which the data for estimating the coefficients are collected. Other limitations of the relationship are that non-algal turbidity (T) is constant with time (Nath, personal communication) and the empirical basis of the relationship restricts its general use for analyzing the functional relationship between chlorophyll *a* and turbidity in aquaculture ponds. Because of the problems associated with the use of the Almazan and Boyd (1979) relationship in ponds with high non-algal turbidity, an investigation was carried out to determine the suitability of an equation developed by Bannister (1974) for determining light extinction coefficients in aquaculture ponds. The Bannister (1974) equation, which is derived from the Lambert-Bouguer law for light extinction in water, expresses the total light extinction coefficient (k_t) as a linear function of non algal turbidity (k_w) and algal turbidity ($k_c c$) (Equation 2).

$$k_t = k_w + k_c c \qquad (2)$$

where c = chlorophyll *a* concentration (mg m^{-3}); k_t and k_w have units of m^{-1} and k_c has units of (mg m^{-3})$^{-1}$. The coefficients k_w and k_c were estimated from the PD/A CRSP Central Database by regressing chlorophyll *a* against the light extinction coefficient (estimated from SDV values using the Poole and Atkins relationship). The range of k_w was 2.22 to 7.13 and the constant k_c was 0.014 ± 0.003. The results for k_c are similar to those reported for natural freshwater systems (Lorenzen, 1980). The equations for calculating phytoplankton production rates in the model were modified to include Equation (2).

Sediment Sub Model: Mineral Soil Processes

The sediment processes incorporated in the model include sedimentation and resuspension, organic matter decomposition, and nitrogen mineralization and loss through leaching as a result of water infiltration. Previous results (Jamu and Piedrahita, 1996) showed that the extent to which the parent mineral soil participates in the sediment organic matter and nitrogen processes may be important for the accurate simulation of these compounds. These results suggested the need to add a mineral soil component to the sediment submodel. Information on the extent to which mineral soil participates in pond sediment processes is lacking. However, with the current pond sediment model it is possible to determine the model boundaries through consideration of the sediment sampling depth for the parameters of interest. The PD/A CRSP uses a 5-cm core sampling depth to determine the nutrient and organic matter content of pond sediment (PD/A CRSP, 1992). The volume of mineral soil involved in sediment nitrogen and organic matter processes is, therefore, defined as the difference between the sampling depth and the depth of accumulated organic matter multiplied by the pond area. Using this definition, the organic matter layer is assumed to be a distinct and separate layer from the mineral layer—an assumption validated by the observations of Munsiri and Boyd (1995). The nitrogen processes occurring in the mineral sediment are similar to those occurring in the organic matter layer. These nitrogen processes include Ficksian diffusion, leaching through water infiltration losses, denitrification of nitrate, and total ammonia-nitrogen adsorption by the soil exchange complex (Jamu and Piedrahita, 1996).

Results

The model was run using environmental conditions, input rates, and fish stocking densities from the Butare, Rwanda, site (Fourth Work Plan, Experiment 3). The three ponds used for model calibration received a weekly input combination of green grass, urea, and chicken manure. The model was run to determine refinements that would improve the accuracy of model simulations for the following parameters: water column organic matter, water column total ammonia-nitrogen, sediment organic matter, sediment total nitrogen, and chlorophyll *a*. The initial concentrations for organic matter, total nitrogen, total ammonia-nitrogen, and chlorophyll *a* used in the model were set at values equal to the concentrations measured in the experimental ponds.

The modified phytoplankton production model was used to simulate chlorophyll *a* for a period of 155 days. The results show that the simulated chlorophyll *a* values were similar to the observed values (Figure 1a).

The results for water column nitrogen (total ammonia-nitrogen) are presented in Figure 1b. These results show that the simulated water column total ammonia-nitrogen concentration was similar to the observed total ammonia-nitrogen concentration. This is an improvement on previous simulations (Jamu and Piedrahita, 1996) which were only able to simulate the nitrogen (nitrate-nitrogen) concentration trend over time—the predicted concentrations differed from the observed values.

The mean (n = 3) initial sediment organic matter and total nitrogen observed in the experimental ponds at the beginning of the experiment were 2.4 ± 1.54% and 0.15 ± 0.04%, respectively. The simulated organic matter (2.8%) and total nitrogen (0.19%) at the end of the experiment were similar to the

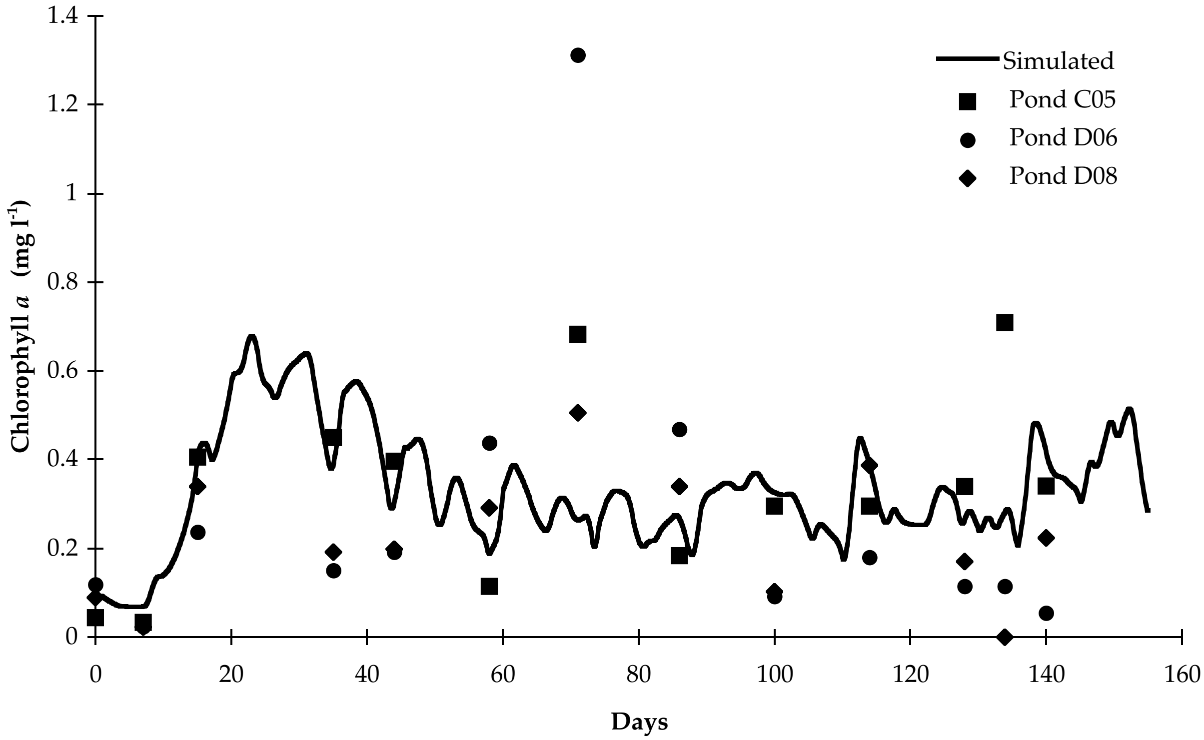

Figure 1a. Simulated chlorophyll *a* concentrations and observed values from three experimental ponds.

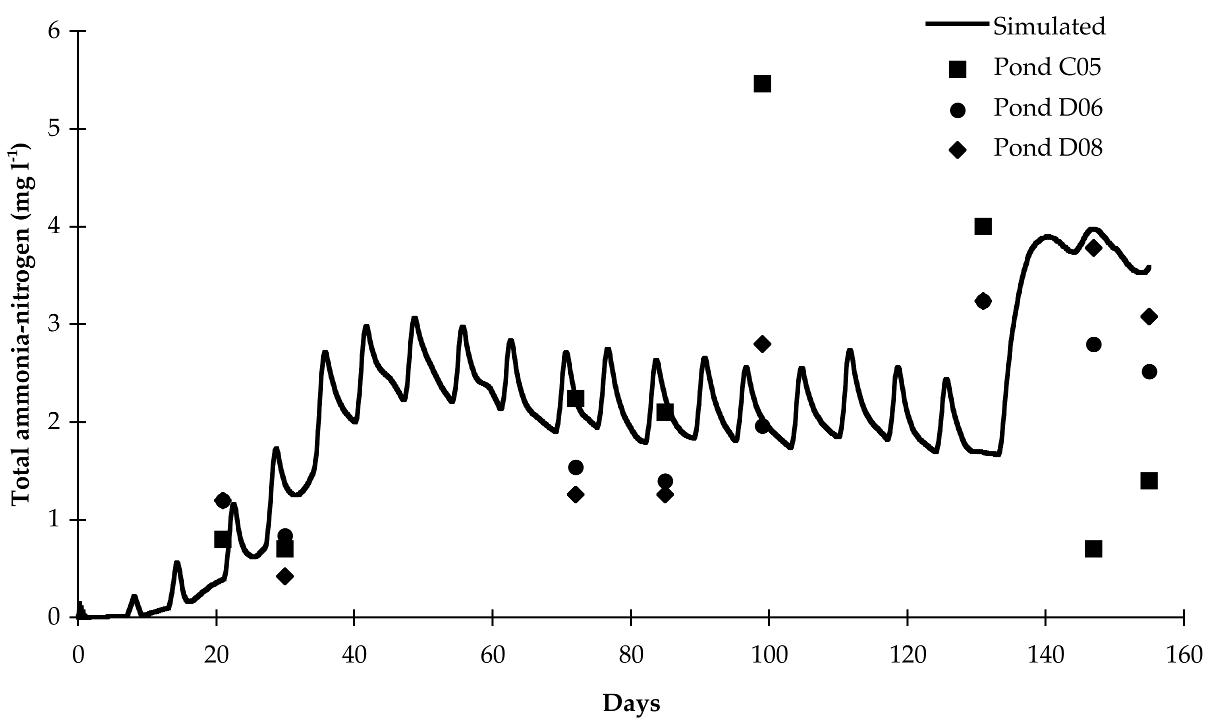

Figure 1b. Simulated total ammonia-nitrogen concentrations in the water column and observed values from three experimental ponds.

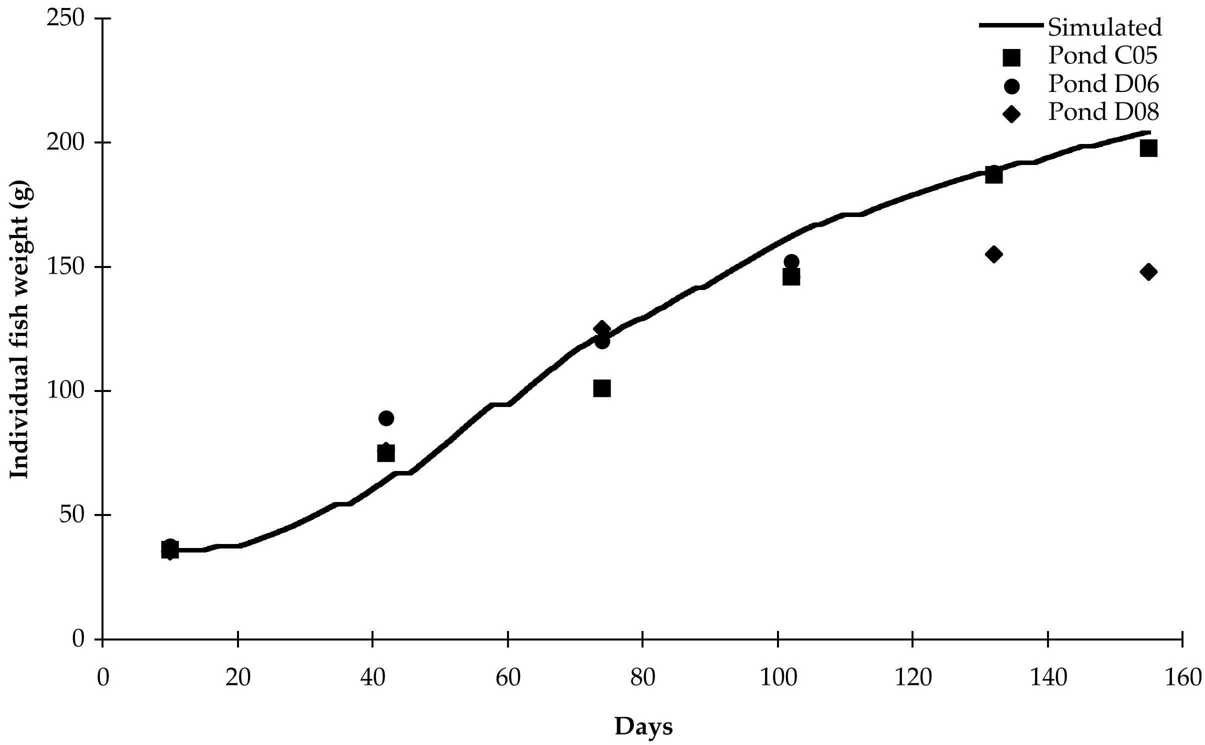

Figure 2. Simulated weights of individual fish and weights of fish from three experimental ponds.

observed organic matter (2.20 ± 1.02%) and total nitrogen (0.18 ± 0.06%) concentrations. The model captured the general trend in the nitrogen concentration; there was a slight increase in total nitrogen concentration, but no significant difference between initial and final total nitrogen concentration. In the case of sediment organic matter, the model predicted a slight increase in sediment organic matter compared with a slight decrease in sediment organic matter concentration observed in the experiment. However, the large standard deviations for the initial and final organic matter concentration suggested that the final simulated organic matter concentration (2.76%) was not significantly different from the observed concentration (2.2 ± 1.02%).

In the PD/A CRSP experiments, sediment organic matter and nitrogen were sampled only three times during the production cycle; at the initial, mid, and end points of the experimental period. The low sampling frequency makes it difficult to compare model output with observed values during the production cycle. In general, the inclusion of the mineral soil component processes (nitrogen adsorption and leaching rates) resulted in model simulations that were similar to the observed values. The previous model runs, which did not consider the mineral soil in the sediment processes, resulted in simulated nitrogen concentrations which were an order of magnitude higher than the observed values (Jamu and Piedrahita, 1996). The modifications that were made to the water column and sediment submodels did not have any negative impacts on the fish growth model as shown by the close agreement between the simulated and observed fish weight (Figure 2).

The modifications to the water column and sediment submodels showed that it is necessary to increase the level of detail/complexity in the model to achieve an acceptable level of model accuracy in the simulation of aquaculture pond nitrogen and organic matter processes.

Anticipated Benefits

The model being developed will provide results that improve our understanding of the relationship between organic matter inputs and sediment nitrogen retention. The results will help farmers identify feeds and fertilizers that promote the development of useful pond sediments. In intensive systems, the results will help in the management of nitrogen, where sediment nitrogen retention could lower ammonia levels in the water column and reduce nitrate loss to surface and groundwaters.

Future Directions

Future work on the development of the model will involve the validation of the model for other data sets and the coupling of the agriculture module to the aquaculture-pond-ecosystem module. The integrated aquaculture-agriculture model is expected to be used to analyze the effects of integration and material recycling on nitrogen retention and system productivity and to identity the possible environmental impacts of aquaculture effluents on agroecosystems.

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