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Aquaculture Pond Modeling for the Analysis of Environmental Impacts and Integration with Agriculture: Model Evaluation and Application to the Ecological Analysis of Integrated Aquaculture/Agriculture Systems

Eighth Work Plan, Aquaculture Systems Modeling Research 1A (8ASMR1A)
Final Report

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Abstract

A model developed to analyze the environmental impacts of aquaculture and the productivity and ecological function of integrated aquaculture/agriculture systems was evaluated using sensitivity analysis and model validation methods. The validated model was used to identify priority areas for future research in integrated aquaculture/agriculture systems and to study the flow of nitrogen in these systems. Sensitivity analysis results showed that the model was most sensitive to maximum photosynthetic rate, aerobic sediment depth, oxygen threshold for aerobic conditions, water infiltration rate, and organic matter sedimentation rate. Model validation was established by the successful replication of observed patterns for individual fish weight, dissolved oxygen, total ammonia nitrogen, sediment organic matter, sediment nitrogen, chlorophyll *a* biomass, and corn grain yield. Application of a qualitative evaluation of research priorities that combined sensitivity analysis and parameter availability identified stocking practices, sediment processes, and water management as priority areas for future research in integrated aquaculture/agriculture systems. Based on the simulation results, the model appears to be appropriate for analyzing the management of organic matter and nitrogen in integrated aquaculture/agriculture systems. The model is also useful for identifying research areas that may be important in the scientific understanding of integrated aquaculture/agriculture systems.

Introduction

The development of an integrated aquaculture/agriculture model was based on existing models of aquaculture ponds and of agricultural crops. Both models were modified extensively to achieve an integrated model that could be executed with data such as those collected under the PD/A CRSP. The integrated model was developed for analyzing the function of integrated aquaculture/agriculture systems and the impacts of aquaculture on its surrounding environment.

Previous progress reports describe various model components. The primary objective in this final report is to summarize the results of model testing (sensitivity analysis and validation) and discuss the implications of simulation results obtained in a set of modeling studies. The focus in the modeling studies was the examination of the effect of cycling pathways on system nitrogen retention and productivity. Details of the model are available in previous progress reports (Jamu and Piedrahita, 1998, 1999) and in Jamu (1998), where sediment changes over long-term (10 year) simulations are also discussed.

Sensitivity Analysis

Sensitivity analysis involves making changes to model rate coefficients singly or in combinations and determining the resulting changes in model output. Sensitivity analysis results are used to identify the most important model parameters, areas for future research, and the level of precision required for measuring system input variables (Kitchell et al., 1977). Sensitivity analysis can also be used to test the robustness of a model.

The integrated aquaculture/agriculture model was subjected to a sensitivity analysis by varying rate coefficients based on the observed variability (± 1 SD) for the selected rate coefficients and parameters (initial values). Where such information was not available, a constant ± 50% adjustment was used. The percentage adjustment was determined on the basis of sensitivity results for aquaculture ponds reported in the literature (e.g., Lanhai, 1997; Schaber, 1996) and the observed variability of the different parameters in the PD/A CRSP database. The response variables for the sensitivity analysis were selected to reflect the objectives of the research with respect to nitrogen cycling and yield productivity. Response variables were also selected on the basis of their utility in aiding the interpretation of the sensitivity analysis results. The sensitivity analysis consisted of varying 22 parameters and determining the response for the following 11 state variables: water column nitrogen, sediment organic matter, nitrogen retention index (N output/N input) (also known as the nitrogen output to input ratio (DeAngelis, 1992)), individual fish weight, crop soil nitrogen, chlorophyll *a* concentration, pond dissolved oxygen, water column organic matter, crop biomass, and terrestrial soil organic matter.

The sensitivity analysis results are presented as a percent change and as a normalized sensitivity coefficient (NS). The normalized sensitivity coefficient is calculated as (Fasham et al., 1990):

$$NS = \frac{\left({\Delta V}/{V_b} \right)}{\left({\Delta P}/{P_b} \right)}$$

where

DV = $(V_b - V)$ = average change of a response variable (e.g., fish weight) over the simulation period

V_b = average value of a response variable for the base run
V = average value of a response variable for the sensitivity analysis run
DP = $(P_b - P)$ = change in model parameter
P_b = baseline value of model parameter and
P = value of model parameter for the sensitivity analysis run

To determine the most sensitive parameters, the normalized sensitivity coefficients were first ranked in descending order based on the absolute value of NS. The determination of the cut-off point between the most sensitive and less sensitive parameters is usually arbitrary. However, in this work, the cutoff point was identified with the aid of quantile plots or Q-Q plots (Swartzman and Kaluzny, 1987). This procedure involved plotting the effects (normalized sensitivity coefficients) against quantiles from a normal distribution. If the plots come from the same normal distribution the quantile plots should be a straight line and any sensitive parameters deviate from the straight line. The quantile plots were not used in a quantitative manner because this required that the data be normally distributed—an assumption that could not be met by the simulated values.

MODEL VALIDATION

The integrated aquaculture/agriculture systems model was validated by graphically comparing model output to observed time series data from experiments conducted in Honduras, Thailand, and Malawi. Where adequate time series data were not available, tabular comparisons were used. The data used for model validation were independent from the data used for model calibration.

Agriculture Component Model

The agriculture component model was validated using data from irrigation trials conducted at the Kasinthula Agricultural Research Station, Malawi (Kauta and Kadwa, 1993). The Kasinthula Agricultural Research Station located at 16°S and 34°E is part of the Malawi National Agricultural Research System. This station is used for research on irrigated tropical agriculture. The data for validating the terrestrial crop model were from trials designed to investigate the effect of water and nitrogen application rates on the yield of corn (*Zea mays*). The treatments consisted of nitrogen fertilization rates as the main factor. Nitrogen was applied as urea at 80 and 160 kg ha^{-1} at planting and 35 days after planting. Water application rates were the second factor in the factorial experiment. Water was applied as a percentage (20%, 40%, 80%, 100%, or 120%) of the base amount (100% of total crop evapotranspiration (Et_0)). The corn was planted during the winter (May to September) and was harvested after 121 days. Malawi crop data were used because of the unavailability of comparable data in the PD/A CRSP database that could be used to validate the behavior of the agriculture model when nitrogen and water rates were varied. Validation of the agriculture model under these conditions is crucial since transfer of nitrogen from the pond and the use of pond water for irrigation are the major pathways for integration.

Aquaculture Component Model

Validation of the aquaculture component model was done using data from PD/A CRSP experiments conducted in Honduras (Third Work Plan, Experiment 3) and Thailand (Fourth Work Plan, Experiment 4) and from a pilot integrated aquaculture/agriculture system in Malawi. The variables selected for validation were individual fish weight, chlorophyll *a* concentration, water column total ammonia nitrogen (TAN), dissolved oxygen concentration (DO), pond sediment organic matter, and pond sediment nitrogen. Details of site descriptions, experimental protocols, and sampling procedures for the PD/A CRSP data are given in Bowman and Clair (1996) and Egna et al. (1995). In summary, the Honduras experiment (PD/A CRSP Third Work Plan, Experiment 3) was designed to investigate the effects of four chicken manure application rates (125, 250, 500, and 1,000 kg^{-1} ha^{-1} wk^{-1}) on fish production and pond dynamics. The experiment at the Bang Sai Fisheries Station, Ayutthaya, Thailand (PD/A CRSP Fourth Work Plan, Experiment 4) was designed to investigate the effects of fertilizing ponds with chicken manure and different levels of supplemental nitrogen fertilization. Three different chicken manure application rates were used and nitrogen was added to maintain an input N:P ratio of 5:1.

The experiments conducted in Malawi were designed to investigate the effects of applying farm plant wastes to ponds and determining the effect on fish yield and sediment organic matter quality and accumulation. The fish species used was the macrophytophagous *Tilapia rendalli* stocked at 2 fish m^{-2}. The experiment was part of an integrated aquaculture/agriculture systems study designed to investigate pond utilization of agricultural wastes, nitrogen cycling, and productivity of integrated aquaculture/agriculture systems. The treatments were as follows: corn bran x leucaena leaf supplement, corn bran x leucaena leaf supplement x plant wastes at 24 kg^{-1} ha^{-1} d^{-1}, and corn bran x leucaena leaf supplement x plant wastes at 42 kg^{-1} ha^{-1} d^{-1}. The treatments follow guidelines for input types and rates used on low-input integrated fish ponds in Malawi (Brummett and Noble, 1995).

The time series data for experiments with three or more replicates were plotted as mean ± 1 SD. The standard deviation was selected for evaluating the model fit to data because it is a fairly robust statistic for representing data spread around the mean. In addition, use of the standard deviation does not require the assumption of conditions that invalidate the use of other statistical methods, e.g., regression for model validation. The model was considered to be adequate or reliable when the model output followed the pattern of observed values and the model simulations were generally within one standard deviation of the replicate data.

MODEL APPLICATION

One of the major objectives for developing ecosystem models is their application as analysis tools for complex systems which otherwise would be difficult to analyze using conventional tools such as field experimentation, inventory monitoring, etc. Of more relevance to integrated aquaculture/agriculture systems is the identification of priority areas for future research and the identification of important processes that could be managed to increase/optimize productivity and efficiency of the system. In this report, the application of the model to identification of priority areas for future research and the use of the model to conduct a modeling study are demonstrated.

Identification of Priority Areas for Future Research

The parameters that would benefit from future research were identified using a qualitative method that combined the rankings of sensitivity analysis results and parameter availability to arrive at the priority ranking of a given parameter/process for future research (Kitchell et al., 1977). Parameter availability considers the observed variability of the parameter, ease of measurement, and source of values for the parameter, i.e., whether parameters were estimated for the species or system under consideration or were extrapolated from another species/system. For example, a parameter that had high variability in field measurements would be ranked as having low availability. If the response variable was sensitive to this parameter then one would rank it high on the priority list for future research. The priority rankings were in three categories that represented parameters with high, medium, and low potential for future research. The parameters that were used in the qualitative evaluation were the most sensitive parameters with respect to nitrogen cycling index, fish weight, crop grain yield, pond (water column and sediment) nitrogen, and organic matter.

Ecological Analysis of Integrated Aquaculture/Agriculture System

The modeling study consisted of simulations of different scenarios designed to study the effects of different cycling pathways on system productivity and nitrogen retention. This provided information necessary to identify the most important linkages between an aquaculture and an agricultural crop. The input scenarios that were simulated for three hypothetical integrated aquaculture/agricultural systems are shown in Table 1. The basic input scenario for the aquaculture component was either chicken manure or crop waste applied as a pond fertilizer. Cycling pathways were added to integrate the aquaculture and the agriculture components until all possible combinations of linkages were achieved (Table 1).

The model was run for a 120-day period using dry season input data from PD/A CRSP experiments conducted at El Carao, Honduras. Model runs simulated tilapia and corn production in the aquaculture and agriculture components, respectively. System variables for the simulation runs were selected to reflect both the ecological performance (biomass yield and nitrogen retention) and impact on marketable product (individual fish weight). The variables selected to assess the effect of cycling pathways were total system nitrogen input (kg N ha^{-1}); gross fish yield (kg ha^{-1}); corn yield (kg ha^{-1}); individual fish weight (g wet weight); total nitrogen yield (kg N ha^{-1}); and nitrogen retention index. The total system nitrogen yield was calculated on the assumption that the agriculture and aquaculture components occupied equal proportions of land totaling one hectare. For testing the hypothesis that integration of aquaculture and agriculture increases system nitrogen retention, the nitrogen retention index appears to be the most appropriate measure of nutrient cycling. The behavior of the nitrogen retention index (DeAngelis, 1992) relative to other ecological measures of nitrogen cycling is known for natural systems.

Table 1. External input scenarios for three different hypothetical integrated aquaculture/agriculture systems.

Farm System	Agriculture Component	Aquaculture Component
1	Inorganic fertilizer @ 160 kg N ha^{-1}	Chicken manure @ 500 kg ha^{-1} wk^{-1}
2	None	Chicken manure @ 500 kg ha^{-1} wk^{-1}
3	Inorganic fertilizer @ 160 kg N ha^{-1}	None

Biological nitrogen fixation was not considered in the nitrogen input term because it was assumed that this process constituted an insignificant nitrogen source relative to other inflow sources. In addition, nitrogen input through wet and dry deposition was also considered to be insignificant. The output term included nitrogen losses through leaching and denitrification. Volatilization was not considered to be a significant nitrogen sink. It was assumed that all harvests were consumed within the farm ecosystem. In order to compare the efficiency of nitrogen utilization between different simulated scenarios and that of agro-ecosystems, the nitrogen retention index was recalculated so that only yield output was considered as a nitrogen output. The recalculation of the nitrogen retention index reflects the shortage of information on estimates of nitrogen leaching losses in agro-ecosystems (e.g., Dalsgaard, 1996).

RESULTS

Because of the large number of response variables used in the sensitivity analysis, the results for the different response variables were combined and only the most sensitive (absolute values) parameters are summarized in Table 2. The results indicate that the model is very sensitive to the water infiltration rate, the maximum photosynthetic rate, the oxygen threshold for aerobic conditions, the organic matter sedimentation rate, and the aerobic sediment depth. The model sensitivity results suggest that these parameters require accurate estimation and/or calibration.

The results on the identification of important processes that are likely to affect system productivity and nitrogen retention are presented in Table 3. These results are based on: a) a comprehensive sensitivity analysis (summarized in Table 2 for the ten most (absolute) sensitive parameters); b) literature reviewed during the development of the model; and c) observations from field experiments. The processes and management activities associated with the initial fish weight, aerobic sediment depth, non-phytoplankton light extinction coefficient, crop irrigation rate, water infiltration rate, and mineral soil organic matter decomposition rate coefficient were identified as the most likely to benefit from future research on integrated aquaculture/agriculture systems. Processes related to the organic matter sedimentation rate coefficient and initial sediment organic matter were found to be of medium research priority. The parameters with a low priority ranking for future research are the oxygen threshold for aerobic conditions, nitrogen mineralization rate coefficient, and the maximum photosynthetic rate. The oxygen threshold for aerobic conditions, despite having a high sensitivity is ranked low on future research priorities because of the high availability of basic information in the literature on this parameter for a wide range of microorganisms and aquatic environments. In general, these results show that research on stocking practices, sediment processes, and water management should be considered a priority for enhancing the scientific understanding of the function of the integrated aquaculture/agriculture system.

Model validation results show that the integrated model was able to replicate the pattern and behavior of observed data for the selected parameters (Jamu, 1998). The results of the crop growth simulations show that simulated maize yield responded to different water and nitrogen application rates. The simulated maize yields were similar to observed values. However, the model did not capture the pattern of phytoplankton dynamics for Ayutthaya, Thailand, and it also failed to capture the decrease in corn yield observed in treatments where nitrogen and water were applied at 160 kg N ha^{-1} and 120% Et_0 respectively. In addition, the model failed to capture the increase in yield with increasing water application rates in fields that were fertilized at 80 kg N ha^{-1}.

The unsatisfactory results for Thailand can be attributed to failure of the model to account for factors such as zooplankton control on phytoplankton populations or preference of phytoplankton species by fish. It was assumed in the model that the phytoplankton biomass consisted of a single assemblage of species with similar physiological and biochemical characteristics. Improving the phytoplankton model to include zooplankton grazing, variability in phytoplankton palatability, and modeling the dynamics of phytoplankton species composition may increase the accuracy of the phytoplankton simulations. The model accurately replicated the pattern of fish

Table 2. The effects of ± 50% or ± 1 SD in different parameter values on different state and output variables. The results show the ten most sensitive parameters ranked according to absolute magnitude of the normalized sensitivity values (NS).

Parameter	Sensitivity Variable	Baseline Value	Sensitivity Value	Parameter Change	Baseline Simulation	Sensitivity Simulation	% Change	NS
Water Infiltration Rate (m d^{-1})	Water column nitrogen	0.007	0	-1 SD	39.89	346.24	767.9	-7.68
Maximum Specific Phytoplankton Production Rate per Unit of Carbon (mg O_2 (mg C)$^{-1}$ h^{-1})	Chlorophyll *a* biomass	0.83	0.91	+1 SD	1.4090	0.9376	-33.46	3.47
	Chlorophyll *a* biomass	0.83	0.75	-1 SD	1.4090	1.8697	32.70	3.39
O_2 Threshold for Aerobic Conditions (mg l^{-1})	Nitrogen retention index	0.2	0.1	-50%	0.0962	0.2243	133.18	-2.66
	Water column nitrogen	0.2	0.1	-50%	39.89	13.51	-66.12	1.32
Organic Matter Sedimentation Rate k (d^{-1})	Water column organic matter	0.05	0.025	-50%	4,307.40	6,925.77	60.79	-1.22
Maximum Specific Phytoplankton Production Rate per Unit of Carbon (mg O_2 (mg C)$^{-1}$ h^{-1})	Dissolved oxygen	0.83	0.91	+1 SD	14.86	13.35	-10.18	1.06
	Crop soil nitrogen	0.83	0.91	+1 SD	151.86	137.46	-9.48	-0.98
Aerobic Sediment Depth (m)	Water column nitrogen	0.001	0	-50%	39.89	2.29	-94.26	0.94
Phytoplankton Digestibility Coefficient (Dimensionless)	Individual fish weight	0.55	0.42	-1 SD	170.73	133.47	-21.62	0.92

Table 3. Summary of a sensitivity analysis of model parameter evaluations and their projected impact on future research on nitrogen cycling and productivity of integrated aquaculture/agriculture systems. Parameters were evaluated qualitatively based on the observed variability of measurements, availability of data for the system, and sensitivity.

Parameter	Sensitivity	Availability	Research Priority
Organic Matter Sedimentation Rate	High	Medium	Medium
Maximum Photosynthetic Rate	High	High	Low
Initial Fish Weight	High	Low	High
Aerobic Sediment Depth	High	Low	High
Non-phytoplankton Light Extinction Coefficient	High	Low	High
Irrigation Rate	High	Low	High
O_2 Threshold for Aerobic Conditions	High	High	Low
Water Infiltration Rate	High	Low	High
N Mineralization Rate	High	High	Low
Initial Sediment Organic Matter	High	Medium	Medium
Mineral Soil Organic Matter Decay Rate	High	Low	High

growth, and overall simulations of individual fish weight were within the range of observed data.

The results of the modeling study on the effects of introducing different organic matter and nitrogen cycling pathways on system productivity and nitrogen retention for the three system management scenarios are presented in Table 4. Recycling of plant wastes to the aquaculture pond in Systems 1 and 2 had a more appreciable effect on the nitrogen retention index, final individual fish weight, and gross fish yield than in System 3 (Table 4). Plant waste recycling also reduced the nitrogen retention index by 11% in Systems 1 and 2 and by 5% in System 3. In System 1, where the corn crop was assumed to be fertilized inorganically, recycling sediment to the agriculture component did not increase the corn yield. In System 2, corn yield increased with successive addition of linkages, and the simulated yield attained when both plant wastes and pond sediments were recycled was equivalent to that of inorganically fertilized corn (Table 4b).

Addition of a cycling pathway for plant wastes from the agriculture to the aquaculture component reduced the nitrogen retention index and increased final fish weight and gross fish yield from 223 to 254 g and 3,793 to 4,320 kg ha^{-1}, respectively. Recycling plant wastes to the aquaculture component in System 3 led to a slight reduction in the nitrogen retention index without a concomitant increase in gross fish yield (Table 4c). Linking the aquaculture and agriculture components through pond sediment and plant waste recycling led to a larger decrease in the nitrogen retention index compared to the recycling of plant wastes alone (Table 4a–4c).

Table 5 compares the simulated nitrogen yield efficiencies (system nitrogen yield/system nitrogen input) for various integrated systems scenarios with observed data reported in

Table 4a. Productivity and nitrogen retention for a hypothetical integrated aquaculture/agriculture farm. Corn crop fertilized at 160 kg N ha^{-1}, chicken manure input to aquaculture component at 500 kg ha^{-1} wk^{-1} (System 1).

Cycling Pathway	**Ecosystem Performance Indicator**				
	N Input (kg ha^{-1})	*N Retention Index* (N_{loss}/N_{in})	*Gross Fish Yield* (kg ha^{-1})	*Corn Yield* (kg ha^{-1})	*N Yield (Fish + Grain)* (kg ha^{-1}) [a]
Irrigation Water	438	1.92	3,793	2,880	57.5
Irrigation Water x Plant Waste	438	1.71	4,320	2,880	63.5
Irrigation Water x Pond Sediment	438	1.99	3,791	2,880	57.5
Irrigation Water x Plant Waste x Pond Sediment	438	1.95	4,321	2,880	63.5

[a] Assumes that fish and corn occupy equal land area in a 1-ha integrated farm.

Table 4b. Productivity and nitrogen retention for a hypothetical integrated aquaculture/agriculture farm. Fish ponds fertilized with chicken manure at 500 kg ha^{-1} wk^{-1}, no external nitrogen input to agriculture component (System 2).

Cycling Pathway	**Ecosystem Performance Indicator**				
	N Input (kg ha^{-1})	*N Retention Index* (N_{loss}/N_{in})	*Gross Fish Yield* (kg ha^{-1})	*Corn Yield* (kg ha^{-1})	*N Yield (Fish + Grain)* (kg ha^{-1}) [a]
Irrigation Water	278	3.11	3,793	2,680	55.1
Irrigation Water x Plant Waste	278	2.75	4,322	2,680	57.5
Irrigation Water x Pond Sediment	278	3.11	3,793	2,703	56.5
Irrigation Water x Plant Waste x Pond Sediment	278	2.79	4,320	2,880	63.5

[a] Assumes that fish and corn occupy equal land area in a 1-ha integrated farm.

Table 4c. Productivity and nitrogen retention for a hypothetical integrated aquaculture/agriculture farm. Corn crop fertilized at 160 kg ha^{-1}, no external input to aquaculture component (System 3).

Cycling Pathway	**Ecosystem Performance Indicator**				
	N Input (kg ha^{-1})	*N Retention Index* (N_{loss}/N_{in})	*Gross Fish Yield* (kg ha^{-1})	*Corn Yield* (kg ha^{-1})	*N Yield (Fish + Grain)* (kg ha^{-1}) [a]
Plant Wastes	160	3.75	3,513	2,880	54.4
Irrigation Water x Plant Waste	160	3.56	3,513	2,880	54.4
Irrigation Water x Pond Sediment	160	3.56	3,513	2,880	54.4
Irrigation Water x Plant Waste x Pond Sediment	160	3.67	3,513	2,881	54.4

[a] Assumes that fish and corn occupy equal land area in a 1-ha integrated farm.

the literature for various agro-ecosystems. Simulated nitrogen yield efficiency for the different integrated systems scenarios in this study ranged from 0.29 to 0.87. Integrated systems that recycled both pond sediments and plant wastes had the highest simulated yield efficiency (0.87) among the integrated farm scenarios modeled. This value was similar to that observed in diversified integrated rice-fish farms (Dalsgaard, 1996). Nitrogen yield efficiencies for integrated systems that were linked through irrigation water only were generally similar to those observed for rice monoculture systems and integrated rice-livestock-fish systems.

DISCUSSION

The largest normalized sensitivity value was obtained when the water infiltration rate was reduced to zero. It has been observed that water infiltration rates in ponds are variable both over time and within any given single site (Teichert-Coddington and Claros, 1994; Chikafumbwa, 1996). Other factors that influence infiltration rates are pond inputs and soil type (Teichert-Coddington and Claros, 1994). In the model, the pond water infiltration rates were assumed to be constant. Although this assumption simplifies the incorporation of the water infiltration rate term in the model, it is incorrect and could result in significant errors in the simulation of water column nitrogen.

One of the uses of the analysis to determine which are likely to be the research areas with the greatest potential benefits is in designing field experiments. The highest priority areas identified are: processes and management activities associated with the initial fish weight, aerobic sediment depth, non-phytoplankton light extinction coefficient, crop irrigation rate, water infiltration rate, and mineral soil organic matter decomposition rate coefficient. PD/A CRSP experiments have addressed some of these questions in the past, while other areas have not received much attention. A possible experiment that could be conducted would look at the effect of pond water removal on pond water quality and fish yield. In such an experiment, water removal timing and amount would be based on predicted irrigation needs for a coupled agricultural crop, as opposed to pond considerations. Another possible experiment would vary the fish stocking density and fish size at stocking. A third experiment could vary the pre-stocking practices of a pond to improve food availability at the time of stocking.

The recycling of agricultural plant wastes to fertilize fish ponds produced the highest (absolute terms) system nitrogen retention index followed by the recycling of both pond sediments and plant wastes. Pond sediment input to inorganically fertilized corn did not lead to further increases in yield. The recycling of pond sediments to the agriculture component had a positive effect on yield of the agriculture component only when the corn crop in the agriculture component was not inorganically fertilized.

It was hypothesized that system nitrogen retention and productivity would increase as more cycling pathways between the aquaculture and agriculture components were introduced. However, the simulation results showed that an increase in nitrogen cycling pathways increased the system nitrogen retention and productivity only when one or both component(s) were nitrogen-limited. Since the incorporation of all possible cycling pathways did not improve the nitrogen retention index and productivity, the number of cycling pathways can not be interpreted as a measure of the improvement in the system's nutrient utilization efficiency. Similarly, lack of corn yield response in inorganically fertilized corn, and the corn yield response to increased organic matter in unfertilized corn, lend support to this hypothesis.

The reduction of the nitrogen retention index when plant wastes were applied to the fish pond could be attributed to a series of feedback processes that ultimately led to the efficient utilization of nitrogen. Presumably, the application of plant wastes enhanced the detrital and phytoplankton food webs that ultimately increased fish growth rates. Increased fish growth rates resulted in higher grazing rates, which stimulated phytoplankton productivity and nitrogen uptake. Also, application of plant wastes enhanced sediment organic matter accumulation rates as the results showed higher sediment organic matter concentrations in ponds receiving plant wastes than in ponds receiving chicken manure and artificial feed inputs alone. The increased sediment organic matter accumulation rates were due to both the high application rates and the large fraction of moderately decomposable organic matter that occur in corn stover relative to chicken manure or artificial feed (Gohl, 1981; Wang et al., 1985). Sediment organic matter has a high cation exchange capacity and therefore more sites for adsorption of cations like ammonium (Boyd, 1995). Therefore, sediment organic matter accumulation translates into higher

Table 5. Simulated and observed nitrogen retention for various agro-ecosystems.

Farm Type	Nitrogen Retention	Source of Data	Reference
Diversified Integrated Rice-Fish Farm, Philippines	0.78–1.36	Field measurements	Dalsgaard, 1996
Extensive Wheat, Straw Returned to Soil	1.00	Various	Frissel, 1978
IRR x PS x F[1]	0.87	Model	This work, Table 4c
IRR x F	0.87	Model	This work, Table 4c
Intensive Wheat, Straw Returned to Soil	0.66	Model	Frissel, 1978
Mixed Arable Crop Livestock, South America	0.53	Model	Frissel, 1978
CM x IRR x PW	0.45	Model	This work, Table 4b
CM x IRR x PS	0.40	Model	This work, Table 4b
Extensive Carp Culture, India	0.14–0.47	Pond N mass balance	Chatterjee et al., 1997
CM x IRR x PW x F	0.33	Model	This work, Table 4a
CM x IRR x PS x F	0.33	Model	This work, Table 4a
Integrated Rice-Livestock-Fish, Philippines	0.22	Model	Schaber, 1996
Rice Monoculture, Philippines	0.17–0.18	Field measurements	Dalsgaard, 1996

[1] CM = chicken manure; IRR = irrigation; PW = plant wastes; PS = pond sediments; F = inorganic N fertilizer.

capacity for ammonia adsorption. Since sediment-adsorbed ammonia is not available for nitrification in the water column (Messer and Brezonik, 1983), the net effect of increased sediment organic matter concentration is a reduction in the amount of ammonia available for leaching and nitrification. Further, the increased ability of ponds receiving plant wastes to retain nitrogen may have been due to the development of the sediment anaerobic layer which decreased overall sediment nitrification rates. A reduction of sediment nitrification rates results in low nitrate seepage and nitrification-coupled denitrification losses (Blackburn and Blackburn, 1992).

ANTICIPATED BENEFITS

Results of the sensitivity analysis, validation, and application show that the model is able to capture the general behavior of important variables in an integrated agriculture/aquaculture system. The model can also be used in research and management of integrated aquaculture/agriculture systems. The model has proven useful in identifying parameters that require accurate field measurements, priority areas of future research, and processes that are important to the scientific understanding of integrated systems. The model can also be used in planning experiments with integrated aquaculture/agriculture systems designed to improve sediment management and overall management of nitrogen and organic matter in aquaculture ponds.

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