Aquaculture Pond Modeling for the Analysis of Integrated Aquaculture/Agriculture Systems

Interim Work Plan, DAST Study 2

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Introduction

Increased adoption of new activities such as aquaculture into existing agroecosystems calls for the application of simulation models to analyze and forecast consequences of new agroecosystem designs (Elliot and Cole, 1989; Edwards et al., 1988). The main objective of integrated systems is to enhance nutrient cycling and energy flow in the system to obtain maximum benefits in the production of food and fiber (Chan, 1993). Integration of aquaculture and agriculture through the use of pond sediment organic matter as a crop fertilizer, and of pond water for irrigation, establishes linkages between aquaculture ponds and crops.

The large body of literature on aquaculture pond nutrient budgets shows that pond sediments are a major sink of nutrients accounting for 65-72% of nitrogen supplied to ponds (Acosta-Nassar et al., 1994; Briggs and Funge-Smith, 1994; Olah et al., 1994; Schwartz and Boyd 1994). Management actions like feeding rates, feed types, organic matter input and fish species reared may affect pond processes such as organic matter settling, resuspension, nitrification, ammonification, and hence quality of sediments. Therefore, sediment-water nitrogen processes, nutrient recycling, resuspension and nitrogen retention in aquaculture ponds are likely to be important in integrated system models.

Energy and nutrient cycling studies have attributed the observed sustainability of integrated systems to high intrasystem nutrient and material cycling (Ruddle and Zhong 1984; Soemarwoto, 1974). However, integrated systems have not been adequately studied because of their complexity (Edwards et al., 1988). In addition, conventional tools for agroecosystem analysis like energy budgets, do not capture the dynamic properties of the systems (Lightfoot et al 1993; Conway 1987). Simulation models are useful tools in the analysis of complex systems and biogeochemical cycling of nutrients (Anderson, 1992; Thornley and Verbene, 1989). Although system modeling techniques are important for future research in agroecosystems, they have yet to be applied to integrated systems having an aquaculture component (Edwards et al., 1988).

The objectives of the work described in this report is to develop a computer model that can be used to analyze and predict nitrogen and organic matter outputs from an aquaculture pond by modifying current pond ecosystem models to explicitly include organic matter and nitrogen processes. The model developed will be linked with an agriculture/crop model, and the resulting integrated model will serve to simulate the flow of organic matter and nitrogen through combined aquaculture and conventional agriculture practices.

Model Structure

The model consists of three primary modules: Fish Pond, Crop, and Terrestrial Soil Nitrogen (Table 1). In turn, each primary module includes several submodels containing state variables describing the system.

The fish pond module is based on worked carried out by the OSU and UC Davis DAST (e.g. Bolte et al., 1994; Giovannini, 1994; Giovannini and Piedrahita, 1994; Culberson, 1993; Piedrahita, 1990). The crop module is primarily based on SUCROS, a general crop growth model (van Kuelen et al., 1982). Soil nitrogen transformations and water balance equations will be added to the crop module to simulate soil organic matter dynamics, nitrogen availability and uptake by crop. Figure 1 shows in a relational diagram how different submodels interact to simulate fluxes and pools of materials and nitrogen. Details of the area in which work over the last year has focused are presented below.

Table 1. Primary models, submodels, and state variables for an integrated aquaculture-agriculture nitrogen dynamics model

Model	Submodel	State Variables
Fish pond	Fish growth	fish biomass, phytoplankton biomass
	Phytoplankton	phytoplankton biomass
	Water quality	water column organic matter, fish biomass
	Feed quality	feed (artificial feed and algae) N concentration
	Feed uptake	
	Sediment	sediment nitrogen and organic matter concentration
Crop	Crop growth	soil nitrogen, soil water content
	N uptake	
Terrestrial Soil	Organic matter	detrital biomass
	soil nitrogen	soil organic matter, crop biomass, soil water content

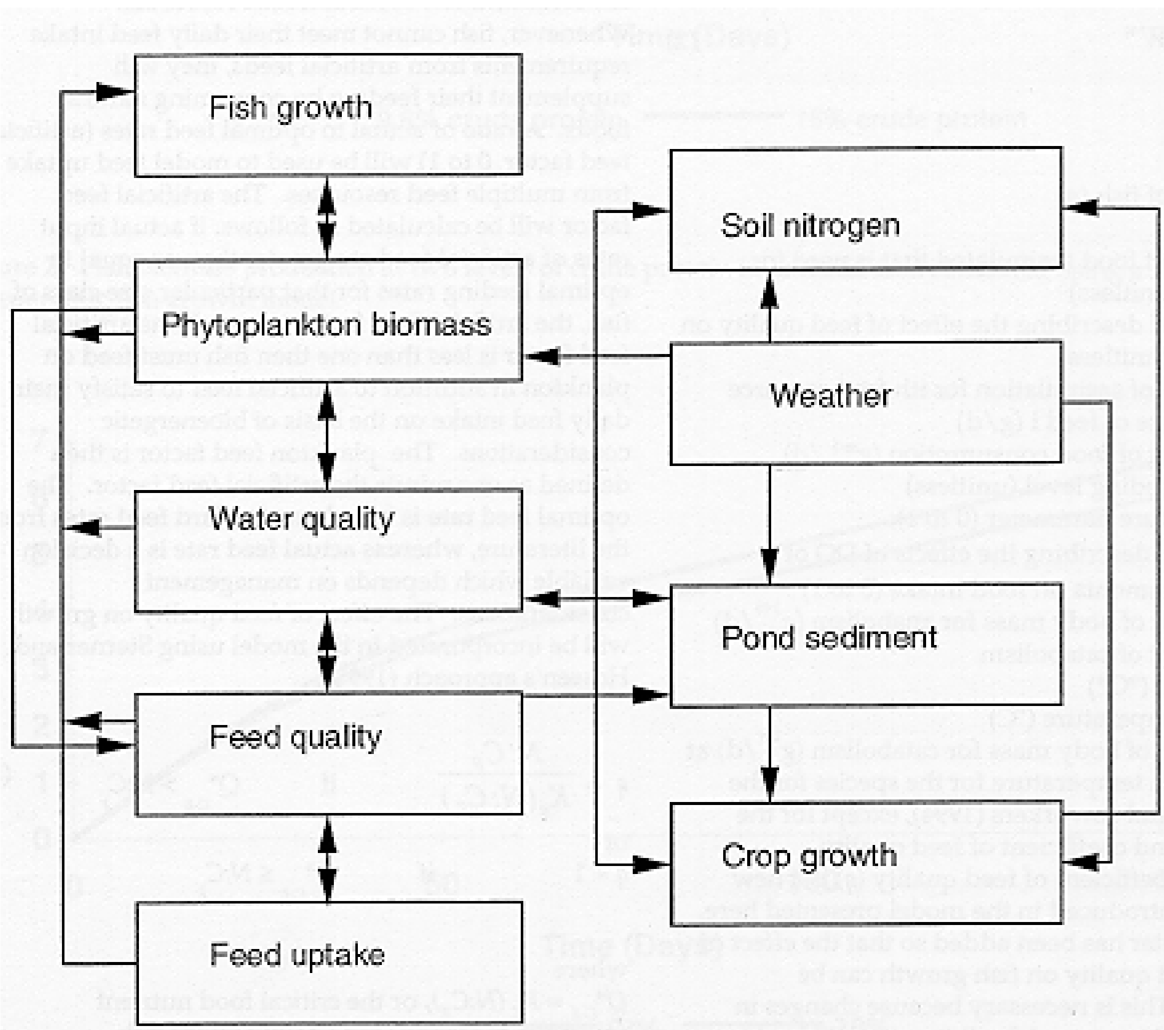

Figure 1. A relational diagram showing connections and feedback between different modules in the nitrogen dynamics model for integrated aquaculture-agriculture systems.

Fish Growth

The fish growth module is adapted from a model developed by the OSU DAST (Bolte et al., 1994). The model describes the growth rate of an individual fish using a differential equation (Ursin, 1967). The OSU DAST model has been modified to include effects of feed uptake from artificial feed and/or phytoplankton on feed quality and feed digestibility. The modified differential equation for fish growth in the new model is:

$$\frac{dW}{dt} = (1-a)q\sum_{i=1}^{k} b_i \frac{dR_i}{dt} - k_{min}e^{[s(T-T_{min})]}W^n \qquad (1)$$

$$\frac{dR_i}{dt} = hf\tau\delta W^m \qquad (2)$$

where
W = weight of fish (g)
t = time (d)
a = fraction of food assimilated that is used for catabolism (unitless)
q = coefficient describing the effect of feed quality on fish growth (unitless)
b_i= efficiency of assimilation for ith feed resource
R^i = intake rate of feed i (g/d)
h = coefficient of food consumption (g^{m-1} /d)
f = relative feeding level (unitless)
τ= temperature parameter (0 to 1);
δ = function describing the effects of DO or unionized ammonia on food intake (0 to 1)
m = exponent of body mass for anabolism (g^{1-m}/d)
k = coefficient of catabolism
s^{min}= constant (°C^{-1})
T = water temperature (˚C)
n = exponent of body mass for catabolism (g^{1-n}/d) at the minimum temperature for the species for the species T_{min} and coworkers (1994), except for the intake rate and coefficient of feed quality.

The coefficient of feed quality (q) is a new parameter introduced in the model presented here. This parameter has been added so that the effect of variable feed quality on fish growth can be simulated. This is necessary because changes in artificial feed types and feeding rates will lead to changes in the diet composition of fish, and will ultimately affect fish growth. The feed intake rate term ($\frac{dR_i}{dt}$) has been modified also, and now incorporates separate food assimilation coefficients (b) for each feed resource instead of an average value for all feed resources in the pond. In addition, feed intake rates from a particular feed resource are calculated based on the assumption that fish will prefer artificial feed regardless of the concentration of other feed resources. This approach is different from that adopted in POND, where feed intake rate of a particular feed resource is calculated using Michalis-Menten kinetic models. In this approach, feed uptake is dependent on the maximum possible uptake, a preference factor (half saturation constant) and the feed concentration. Experimental evidence (e.g. Brummett, 1994; Schroeder, 1978) suggest that tilapias prefer artificial feed to natural feed under culture conditions. Therefore, an assumption is made for the model that fish will take artificial feed independent of the concentration of natural feed resources. Whenever, fish cannot meet their daily feed intake requirements from artificial feeds, they will supplement their feeding by consuming natural foods. A ratio of actual to optimal feed rates (artificial feed factor, 0 to 1) will be used to model feed uptake from multiple feed resources. The artificial feed factor will be calculated as follows: if actual input rates of artificial feed are greater than or equal to optimal feeding rates for that particular size class of fish, the artificial feed factor is one. If the artificial feed factor is less than one then fish must feed on plankton in addition to artificial feed to satisfy their daily feed intake on the basis of bioenergetic considerations. The plankton feed factor is then defined as one minus the artificial feed factor. The optimal feed rate is based on standard feed rates from the literature, whereas actual feed rate is a decision variable which depends on management considerations. The effect of feed quality on growth will be incorporated in the model using Sterner and Hessen's approach (1994):

$$q = \frac{N{:}C_F}{K_c(N{:}C_Z)} \qquad \text{if} \qquad Q^*_{C-E} > N{:}C_F \qquad (3)$$

or

$$q = 1 \qquad \text{if} \qquad Q^*_{C-E} \leq N{:}C_F$$

where
$Q^*_{C-E} = K_C\,(N{:}C_Z)$, or the critical food nutrient (nitrogen to carbon) ratio below which fish production would be partially limited by nitrogen.
$N{:}C_F$ = nitrogen to carbon mass ratio in food
K = gross growth efficiency of fish
$N{:}C_Z$ = nitrogen to carbon ratio in fish

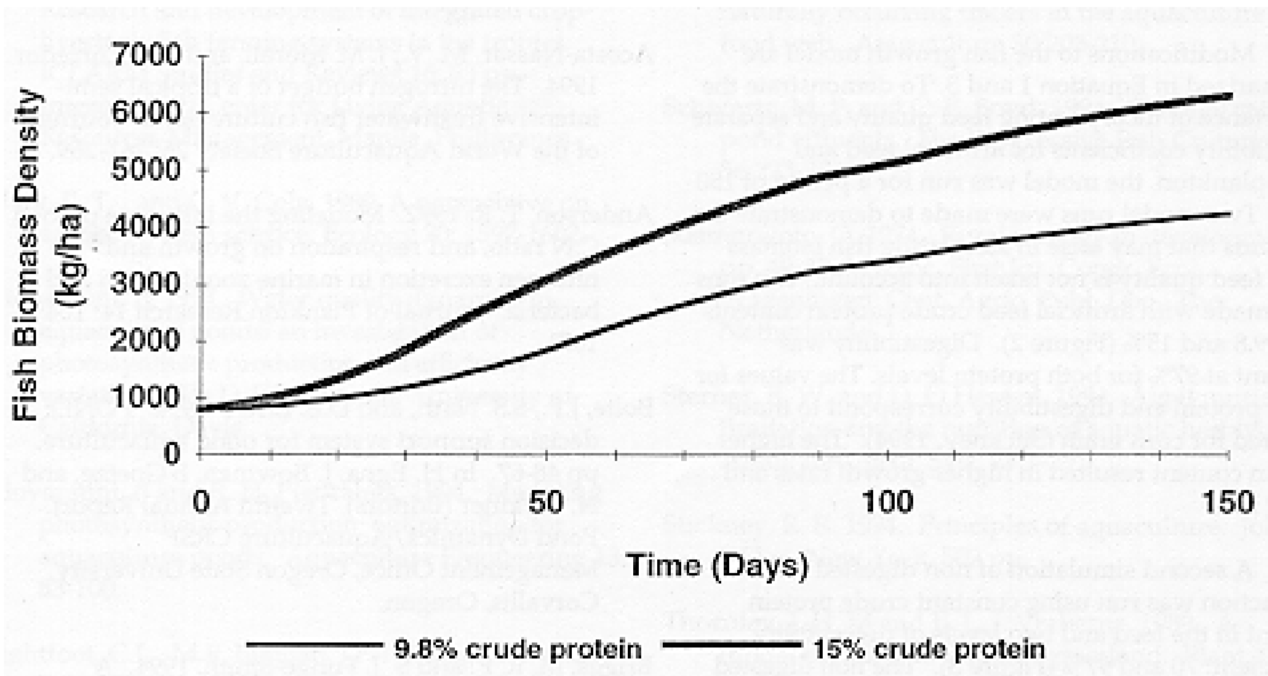

Figure 2. Fish biomass production at two levels of crude protein in artificial feed simulated using a modified bioenergetic fish growth model.

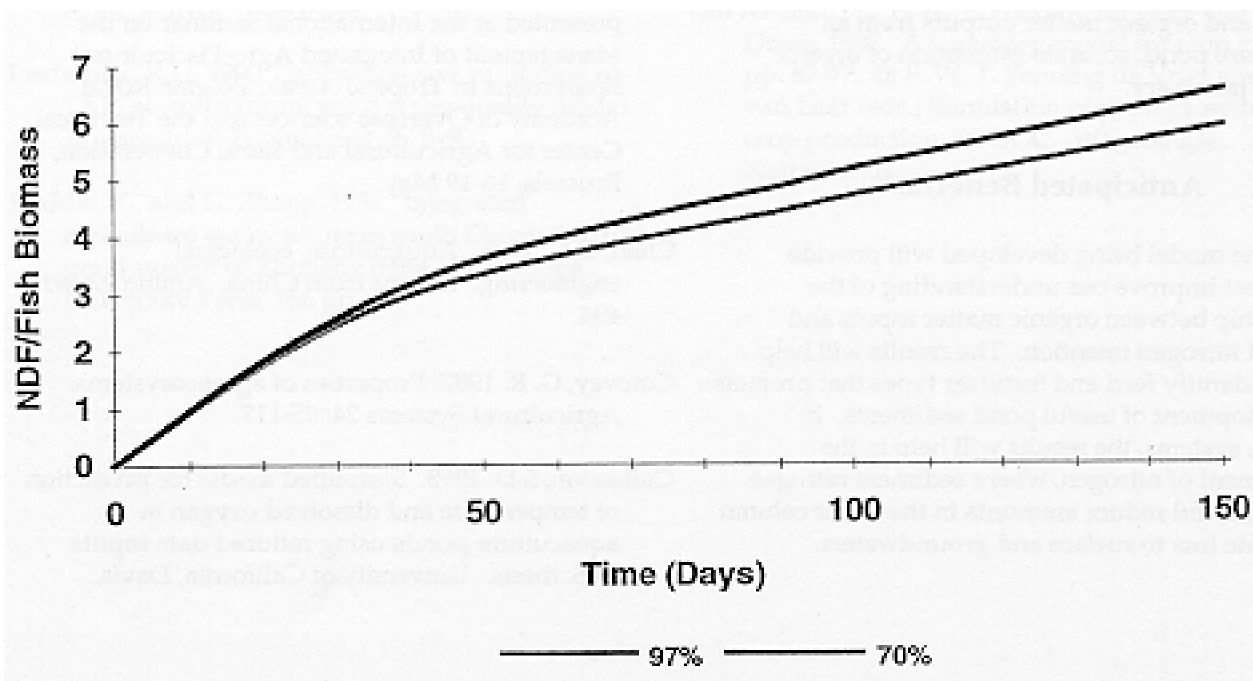

Figure 3. Simulated non digested feed (NDF) production using two different digestibility coefficients. NDF is normalized for fish biomass by dividing NDF with fish biomass.

Results and Discussion

Modifications to the fish growth model are summarized in Equation 1 and 3. To demonstrate the importance of incorporating feed quality and separate digestibility coefficients for artificial feed and phytoplankton, the model was run for a period of 150 days. Two model runs were made to demonstrate the problems that may arise in simulating fish biomass when feed quality is not taken into account. The runs were made with artificial feed crude protein contents set at 9.8 and 15% (Figure 2). Digestibility was constant at 97% for both protein levels. The values for crude protein and digestibility correspond to those reported for corn grain (Stickney, 1994). The higher protein content resulted in higher growth rates and larger fish.

A second simulation of non digested feed production was run using constant crude protein content in the feed and two levels of digestibility coefficient: 70 and 97% (Figure 3). The non digested feed was normalized for fish biomass. The differences in production of non digested feed at the two digestibility coefficients demonstrate that potential errors could be incorporated in organic matter / nitrogen pools and fluxes when an average coefficient is used for feed items. Since one of the objectives of the model is to analyze and predict nitrogen and organic matter outputs from an aquaculture pond, accurate estimation of organic matter is necessary.

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 feed and fertilizer types 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 reduce ammonia in the water column and nitrate loss to surface and groundwaters.

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