Pond Dynamics/Aquaculture Collaborative Research Support Program

Fifteenth Annual Technical Report

1 August 1996 to 31 July 1997

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I. Introduction

The current reporting period, 1 August 1996 through 31 July 1997, is the first year of operation under the PD/A CRSP *Continuation Plan 1996-2001* and of the CRSPs Eighth Work Plan. This report is a collection of research papers summarizing activities described in the Eighth Work Plan and its predecessor, the Interim Work Plan. In addition, it contains several Special Topics research reports. The companion to this volume is the Fifteenth Annual Administrative Report which highlights program management and research support activities, and includes summaries of program history, staff, finances, and publications. It also contains the abstracts of all technical reports included in this volume.

Historical Overview

The PD/A CRSP was initiated formally on 1 September 1982 as a Title XII program under the International Development and Food Assistance Act of 1975. Since its inception, the goal of the CRSP has been to improve the efficiency of pond production systems through sustainable aquaculture. The strategy adopted by the CRSP in pursuit of this goal has involved the development of a comprehensive research agenda aimed at understanding and improving the efficiency of pond culture systems. The centerpiece of this strategy was the Global Experiment.

The Global Experiment was intended as a comparative study of aquaculture pond dynamics—one that would begin to explain how and why ponds at different geographic locations function differently, and how the management of those ponds might be adapted to different sets of environmental conditions to optimize production. Hence, a common set of experiments was implemented globally, following a standardized experimental protocol at a number of research sites around the world. Over the years, the specific objectives of each Global Experiment, conducted once during each biennial work plan, were modified based on previous research results and current information needs, while continuing to further investigate the original charge.

As CRSP research progressed through the 1980s, questions surfaced that differed from site to site and would need to be addressed with specific production optimization experiments. This family of experiments, separate from the standardized Global Experiment, yet performed concurrently with it, also had global implications. After the first few years of production research, the need for economic analyses of pond aquaculture systems became apparent. Previous research had relied on many, often tenuous, assumptions about the dynamic mechanisms regulating pond productivity and pointed to the inadequacy of the existing database. To find out if contemporary pond management practices were in fact the most efficient, CRSP researchers evaluated production methods. An extensive comparison of the socioeconomic dimensions of CRSP production techniques among sites is helping CRSP researchers to understand the impacts of socioeconomic influences on their work. A third research question developed out of the collaboration with Honduran shrimp farmers and led to the investigation of the environmental effects of effluents on receiving waters.

CRSP participants also decided that the comprehensive analysis and interpretation of global data would be greatly enhanced through the formation of an independent team of researchers who could devote their efforts to this type of analysis. This task force was formally established in 1986 as the Data Analysis and Synthesis Team (DAST). The charge of the DAST is to systematically analyze pond processes and to develop computer models that reflect our growing understanding of pond systems. The DAST members are more than end-users of the database; rather, they participate actively in the design process of the next cycle of Global Experiments.

The multitude of the data collected by the Global Experiment and other investigations are available through the PD/A CRSP Central Database, which is the largest database containing standardized data on warmwater aquaculture. To facilitate information dissemination the Central Database is now electronically accessible at two locations on the

Worldwide Web: the PD/A CRSP Internet Web Site (http://osu.orst.edu/dept/crsp/homepage.html) and the Oregon State University (OSU) Bioresource Engineering Web Site (http://biosys.bre.orst.edu/crspDB).

Current Research Program

The *Continuation Plan 1996-2001* listed seven constraints to aquacultural development: inefficient and inconsistent aquacultural productivity, negative environmental effects resulting from aquaculture operations, a poor understanding of social and economic factors, insufficient human capacity development, poor or outdated information management, limited networking capacities, and political and structural inadequacies. The PD/A CRSP developed an integrated approach to address these constraints by constructing a program based on two building blocks: production systems research and capacity building research support activities. Production systems research addresses the first three constraints through the following research areas: production optimization, environmental effects, and social and economic aspects. Research support activities respond to the fourth through sixth constraint through education development, information management, and networking which are reported in the Fifteenth Annual Administrative Report. The seventh constraint, political and structural inadequacies, can only be indirectly addressed by a research program such as the CRSP.

Mr. Mathias Wafula was Head of Station at Sagana Fish Farm, a new CRSP research site in Kenya, during the reporting period. He is now Assistant Director of Fisheries for Nyanza and Western Provinces.

Research areas are further subdivided into specific research themes. Research areas and their respective themes are listed here:

1. Research Area:
   Production Optimization

   Research Themes:
   Pond Dynamics
   Feeds and Fertilizers
   Reproduction Control
   Aquaculture Systems Modeling
   New Aquaculture Systems/New Species

2. Research Area:
   Environmental Effects

   Research Themes:
   Effluents and Pollution
   Appropriate Technology
   Responsible Science Policy
   Geographic Information Systems:
   Planning, Policy, and Global Data Analysis

3. Research Area:
   Social and Economic Aspects

   Research Themes:
   Marketing and Economic Analysis
   Adoption/Diffusion
   Food Security
   Regional Analysis:
   Human-Environment Interactions
   Decision Support Systems
   Product Diversification

The current Global Experiment, fundamental to the operation of the CRSP, focuses on the optimization of nutrient inputs into pond systems and falls into the research theme of Feeds and Fertilizers. In addition, current research is conducted in the following research themes: Pond Dynamics, Feeds and Fertilizers, Reproduction Control, Aquaculture Systems Modeling, New Aquaculture Systems/ New Species, Effluents and Pollution, Marketing and Economic Analysis, Adoption/Diffusion, and Decision Support Systems.

Other changes instituted under the new grant include the addition of two new prime sites, Kenya and Peru, to the Host Country sites at which the CRSP was active under the previous grant, i.e., Honduras, Rwanda, Thailand, and the Philippines. The CRSP was also previously active in Egypt under a separate grant. In addition to scheduled research activities, researchers at each new site also collect baseline data to characterize climatic conditions and water and soil properties. Research at the Kenya site continues the line of inquiry previously developed for the former CRSP site in Rwanda on the effect of supplemental feeds on tilapia production while research at the Peru site emphasizes the development of new aquaculture species. The Philippines, formerly a companion site to Thailand, will take on prime site functions as soon as the current search for a lead institution has been completed. Activities in Thailand focus on regional concerns, e.g., production of larger sized tilapia and environmental effects of aquaculture. Investigations in Honduras continue to center around the effects of shrimp aquaculture on the Gulf of Fonseca and the further development of tilapia aquaculture.

Special Topics Research

The Special Topics component of the CRSP was created to provide opportunities for host country and US researchers to collaborate on original research directed toward the needs and priorities of each host country on an ad hoc basis. The intent is to strengthen linkages and contribute to the development of research capabilities within host country institutions by providing opportunities for scholarly involvement of faculty and advanced students. This component also provides host country institutions and agencies with access to the human resources of the CRSP in seeking solutions to short-term local problems.

Although Special Topics Research projects are an important part of the CRSP, they are not a major component in terms of funding support or time expenditure. Twenty to 25 percent of each researcher's time typically is devoted to this activity. The CRSP places a high priority on its long-term research agenda. Host country institutions and USAID Missions, however, often consider basic research activities such as the Global Experiment to be of low priority. Consequently, administrators in the host countries sometimes have difficulty justifying participation in the CRSP. The CRSP support for the Special Topics Research activities provide incentives for their institutions' participation in the CRSP.

CRSP Work Plans

From the CRSPs beginning, the Technical Committee (TC) of the PD/A CRSP has been responsible for developing technical plans to guide the research efforts of each experimental cycle. During the first three cycles of the program, when global experiments were the main emphasis, CRSP Work Plans were developed annually. The First Work Plan specified a standard protocol for the preparation and stocking of ponds at all locations. Research in the Second Work Plan compared the responses of ponds receiving organic fertilizers with the responses of ponds that received inorganic fertilizers. Experiments described in the Third Work Plan investigated the effects of varying levels of organic fertilizers on pond dynamics.

In response to recommendations of the External Evaluation Panel (EEP), a CRSP advisory body, during the first Triennial Review, the program adopted a biennial work plan schedule beginning with the Fourth Work Plan. Two-year operating cycles allow more time for completion and evaluation of experiments before plans for the next cycle must be completed.

Although the research program has evolved so that the Global Experiment and site-specific experiments are conducted at the various sites, the concept of a standard protocol for research at all sites endures. The standard protocol was initially introduced as a part of the First Work Plan and has been refined with each subsequent Work Plan. In 1992 it finally evolved into the PD/A CRSPs *Handbook of Analytical Methods*, compiled by the

Materials and Methods Subcommittee of the TC and distributed to CRSP participants.

The Fourth Work Plan included tests of specific hypotheses formulated after review of the first three cycles of CRSP research. Special attention was paid to the economic aspects of CRSP pond management procedures. Further, the DAST started to systematically use the Central Database.

The Fifth Work Plan was developed by the TC in May 1989, and encompassed research efforts carried out between 1 September 1989 and 31 August 1991. In addition to the Global Experiment, each site proposed various studies that addressed specific aquaculture needs of the host countries. Field experiments with farmer-cooperators were initiated, allowing researchers to evaluate their strategies under working conditions, and strengthening the linkage between research and practice. Economic analysis became another tool by which the CRSP measured the quality of its research achievements. The DASTs efforts focused on refining models and developing fertilizer guidelines.

The Sixth Work Plan, spanning the period 1 September 1991 to 31 August 1993, was approved at the Ninth CRSP Annual Meeting in May of 1991. A 20 percent funding increase allowed the CRSP to broaden its research scope. Nine supplemental projects were included in the Sixth Work Plan. One of these studies was a preliminary investigation of women's participation in fish culture activities in Rwanda. This study in turn attracted a buy-in from USAIDs Women In Development program (PPC/WID) to perform more complete investigations on the role of gender in fish culture in Rwanda. Also, under the auspices of the Thailand team, research activities were re-initiated in the Philippines.

Under the Seventh Work Plan, the CRSP resumed its original investigation of pond dynamics in brackish water systems, a line of research that had been temporarily suspended when the CRSPs brackish water sites in Panama and the Philippines were lost in 1987. The Seventh Work Plan also introduced biotechnology, and its strong potential to aid aquaculture industries both domestically and abroad, as a new research focus. Experiments originally scheduled to be conducted in Rwanda were reassigned to different sites after the outbreak of civil war. The Africa team regrouped and developed a revised Seventh Work Plan whose experiments are currently conducted in Honduras and the United States. In addition, research on the influence of elevation on tilapia production originally conducted in Rwanda continues in the Philippines.

The Interim Work Plan covered experiments that were conducted during the transition year (May 1995 through April 1996). This deviation from the usual biennial Work Plan format resulted from delays in the grant renewal process. The Interim Work Plan allowed the successful transition from the program's third grant to the fourth grant and the Eight Work Plan.

The CRSPs Eighth Work Plan, describing activities to be conducted by the CRSP during the period 1 August 1996 to 31 July 1998, was developed under a new process calculated to bolster the scientific rigor of the program. Previous work plans were developed by the researchers and reviewed by the TC. For the Eighth Work Plan, the Program Management Office developed a Request for Proposals (RFP) with input from the TC, the EEP, and the Board of Directors. This RFP was distributed to member institutions and solicited proposals for the research themes mentioned in the *Continuation Plan*. Incoming proposals were reviewed by external and internal referees. These evaluations were used by the program's advisory bodies to determine successful proposals and to recommend them to the Management Entity for funding.

The investigations contained in the Eighth Work Plan reflect the broadening of research which was proposed in the *Continuation Plan 1996-2001* as well as increased integration among sites. In addition to specific research activities implemented at prime sites in Central America, South America, East Africa, and Southeast Asia, the Eighth Work Plan includes, for the first time, work plans for cross-cutting research. Cross-cutting research is research that may be conducted at one or more PD/A CRSP sites, and whose results may have wider application than results from prime and companion site investigations. This research builds upon and expands research results obtained through earlier PD/A CRSP research.

II. Research Program Accomplishments

The *Continuation Plan 1996-2001* identified three areas of aquaculture production systems research. These are further subdivided into research themes designed to address the factors constraining the development of sustainable aquaculture. The research outlined in the Eighth Work Plan includes nine of the 15 themes listed in the *Continuation Plan*. Cross-cutting research projects represent six of the research themes identified in the *Continuation Plan 1996-2001*: Pond Dynamics; Reproduction Control; Marketing and Economic Analysis; Decision Support Systems; Aquaculture Systems Modeling; and Adoption/Diffusion; prime site projects represent these and three additional research themes: Effluents and Pollution (Central America), Feeds and Fertilizers (Central America and Southeast Asia), and New Aquaculture Systems/New Species (South America).

Pond Dynamics studies included the continued development of a pond soil classification system that can be utilized across a diversity of sites. Additionally, the data collected to refine this delineation system for pond soils further contributes to the knowledge base regarding the chemical characteristics of soil profiles that can be used in developing a system of pond soil taxonomy used in traditional soil science.

Special Topics Research in Feeds and Fertilizers involved continued testing of the effects of feed protein content on the semi-intensive production of *Penaeus vannamei* in Honduras, the evaluation of supplementary diets for tilapia culture in North Vietnam, and the identification of low cost supplemental feeds for tilapia cage and pond culture in the Philippines.

Reproduction Control research focused on the development of androgenesis techniques for the monosex production of tilapia and the determination of the optimal treatment conditions for masculinizing Nile tilapia (*Oreochromis niloticus*) through immersion in 17α-methyldihydrotestosterone.

Aquaculture Systems Modeling research was directed at enhancing an integrated aquaculture/agriculture model to include relationships between carbon input and sediment quality in aquaculture pond dynamics. Research also led to the development of an aquaculture pond model designed to analyze environmental impacts through the prediction of temperature and dissolved oxygen in stratified fish ponds. Special Topics Research produced two bioenergetics growth models—one that simulates Nile tilapia growth in an integrated culture system and another that incorporates limiting nutrients and standing crop in its simulations of tilapia growth.

Within the Marketing and Economic Analysis theme, a "safety first" model that explicitly addresses risk factors has been developed to analyze the integration of CRSP-developed pond fertilization schemes into Honduran shrimp and tilapia farming systems. Impact and welfare analysis models were also designed so that the social and economic returns attributable to PD/A CRSP technologies can be determined.

Adoption/Diffusion research involved the development of a qualitative study designed to trace the career and educational pathways of students, either directly or indirectly funded by the PD/A CRSP, to determine how students have affected the transfer of CRSP technological and financial resources.

Decision Support Systems research lead to the improvement of the user interface of POND© software. In addition, POND© was refined to enable users to compare production efficiencies at different levels of fertilization and feeding with feed types of varying moisture, protein, and energy content.

Studies in Thailand and Honduras sought to address the impacts of effluents associated with tilapia and shrimp culture, respectively. At the Asian Institute of Technology researchers assessed the amount of nitrogen, phosphorus, and solids discharged from pond waters and evaluated five fish harvest techniques to determine which would most effectively reduce the loading of nutrients and solids in effluent waters.

Since 1993, the PD/A CRSP has participated in a collaborative effort with the Honduran government, local and international educational institutions, and Honduran shrimp farmers to monitor estuary and embayment water quality in the Gulf of Fonseca. Data collected can be used to detect improvements or declines in water quality, formulate and validate numerical estuarine models to predict future estuarine environmental conditions, and estimate estuary carrying capacity by combining farm chemical budgets and estuarine fluid dynamics. These efforts are ongoing.

In Peru, the need to evaluate the aquaculture potential of local and native species and develop appropriate culture technologies has been identified. Currently PD/A CRSP researchers are rearing *Piaractus brachypomus* to contribute to the limited production technology data existing regarding Peruvian aquaculture species and culture technologies.

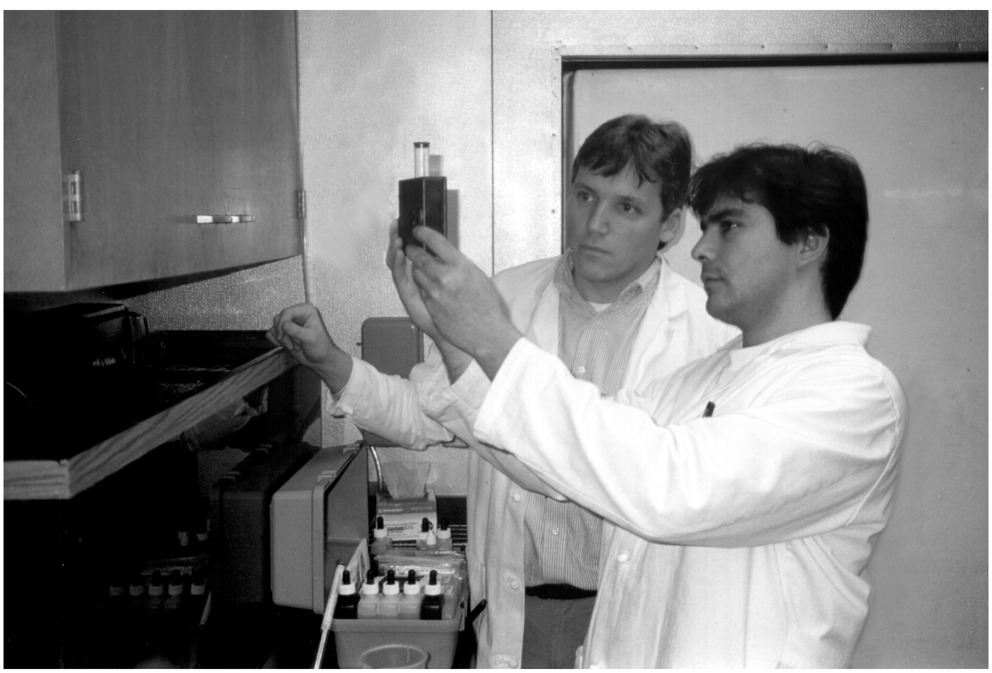
This annual technical report also presents research results from the Interim Work Plan, which covered the period 1 September 1995 to 31 July 1996, in addition to Special Topics Research. Interim Work Plan research included the continued testing of an integrated rotational aquaculture system designed in Thailand, and Special Topics Research involved the development of two bioenergetics growth models.

The technical reports presented here are divided into two major sections: Global Research and Regional Research. Global Research encompasses cross-cutting research, while the Regional Research section presents investigations, including Special Topics Research, conducted at each host country field site in Central America, South America, East Africa, and Southeast Asia. Information related to other aspects of each of the projects—i.e., institution building, linkage development, publications, and other items of significance—is presented in the companion volume, the 15th Annual Administrative Report, which can be ordered from the Program Management Office in Corvallis, Oregon.

III. Global Research

The CRSP conducted global research on the following research themes: Pond Dynamics, Reproduction Control, Marketing and Economic Analysis, Adoption/Diffusion, Aquaculture Systems Modeling, and Decision Support Systems. Auburn University PD/A CRSP scientists elaborated on a classification system to describe pond soil horizons. Soil samples collected from CRSP sites in Thailand and Honduras were analyzed and compared for moisture content, dry bulk density, color, wet and dry soil pH, exchangeable acidity, particle density, total carbon and nitrogen, total phosphorus, total sulfur, and acid-extractable phosphorus and metal ions. Results of soil analyses verified that the classification system could be used to delineate pond soil horizons at a diversity of sites. This system, which provides a framework for the characterization of pond soils, promises to yield soil descriptions that are essential for future PD/A CRSP research and will assist in the refinement of pond management strategies.

Currently PD/A CRSP reproduction control research is aimed at developing monosex tilapia populations through the investigation of immersion treatments for the masculinization of tilapia and androgenesis techniques for the production of YY male tilapia. Several advantages are associated with the monosex production of tilapia: fish growth is enhanced, unwanted tilapia reproduction is prevented, and yields are increased. One way to masculinize tilapia is to administer hormones in their diet; however, the following problems can occur with the use of this technique: 1) uneven hormone exposure of tilapia; 2) high variability in the percent males produced; 3) worker exposure



Oregon State University researchers Martin Fitzpatrick and Wilfrido Contreras sample water quality from tilapia brood tanks.

to steroids (via contact with skin or through the air while feeding); 4) steroidal contamination of the pondwater and sediment and/or the surrounding terrestrial environment; 5) lengthened period of time required for masculinization; and 6) steroid exposure of untargeted organisms. An alternative sex reversal technique that may address the limitations of hormone-treated feed is the immersion of tilapia fry in steroid solutions. Previous CRSP studies of steroid immersion demonstrated that immersion for three hours in 17α-methyldihydrotestosterone (MDHT) on days 10 and 13 post fertilization resulted in the masculinization of Nile tilapia.

PD/A CRSP studies continued to focus on short-term immersion therapy at Oregon State University (OSU) and progressed according to schedule. Researchers tested the effects of: 1) rearing density on the efficacy of MDHT immersion; 2) MDHT immersion treatments applied on a single day post fertilization rather than on two different days post fertilization; and 3) immersion treatments using trenbolone acetate (TBA). Results of this study supported outcomes of previous studies that successfully demonstrated the use of short-term immersion treatments and revealed that a single immersion in MDHT on day 13 post fertilization was an effective procedure for masculinizing tilapia. Findings of this study in comparison with previous research results also suggest that masculinization outcomes may improve with longer duration immersion treatments. Tilapia were stocked at 33, 67, 100, and 200 fish l^{-1} and immersed in 500 μg l^{-1} MDHT. Stocking density also affected the sex reversal outcomes—a stocking density of 33 fish l^{-1} resulted in 80.3% males, whereas the 67 and 100 fish l^{-1} stocking densities resulted in 71.1% males, and the 200 fish l^{-1} stocking density resulted in 64.5% males. Two 2-hour immersions in TBA resulted in greater than 90% males in a female-biased brood as compared with 20% males produced in two 2-hour immersions in 17α-methyltestosterone (MT). Additionally, experimental results suggest that the period of sensitivity to steroid-induced masculinization for *Oreochromis niloticus* occurs several days after the initiation of feeding.

Scientists at the University of Oklahoma submitted a progress report describing work geared toward the development of androgenesis techniques applicable to tilapia. Research was delayed and will overlap with the period of the Ninth Work Plan and only initial experimental results are presented regarding the production of androgenotes. To ensure that freshly produced gametes are available for chromosome manipulation, the effects of photoperiod manipulation on the spawning of Nile tilapia (*Oreochromis niloticus*) were evaluated. Tilapia ovulated 9.5 to 13.5 hours after a controlled, northwest, light-on cycle of a 20 L:4 D photoperiod, which confirmed that tilapia ovulation is light cycle sensitive and that photoperiod manipulation is a viable technique for determining stripping time. To perform chromosome manipulations, researchers also developed a tau curve based on a temperature-related rate of development for tilapia. A reasonable first estimate of a tau curve was derived for Nile tilapia—the mean mitotic interval during early synchronous cleavage was between 73.5 and 30 min at 20.6 and 27.5°C, respectively. Future research efforts will be directed toward refining androgenesis methodology and will include identifying more suitable egg incubation techniques, standardizing the thermal shocking of eggs using the working tau curve, determining UV dosage for the deactivation of the female genome, and selecting broodstock with a visual genetic marker for future androgenetic studies.

Marketing and Economic Analysis research activities at the University of Arkansas, Pine Bluff, are progressing according to schedule. PD/A CRSP scientists are presently involved with a study focused on technology adoption and the quantification of economic and social returns associated with CRSP-developed technologies. Many factors—changing market structures, the cost and returns of a given technology, environmental conditions, and established farm practices—influence a fish farmer's decision to adopt a new technology. Researchers are seeking to improve the integration of CRSP technologies and are developing a "safety first" model that will analyze, through the use of survey data collected from shrimp and tilapia producers, the integration of pond fertilization schemes into shrimp and tilapia farming systems in Honduras. The model addresses the question of the sustainability of fertilization schemes by encompassing a broad range of perspectives—the environment, economics, known risk factors, and food security.

To quantify the social and economic returns associated with the adoption of CRSP technologies by Honduran shrimp and tilapia farmers, researchers have designed impact and welfare analysis models to evaluate two specific CRSP technologies: feed regimes recommended to shrimp producers and sex reversal techniques utilized by tilapia producers. The results obtained from these welfare economics models are potentially useful in developing policy recommendations and in evaluating the social impact of CRSP research.

Pond aquaculture models can be used to compare the effects of different management regimes on fish yields, the economic efficiency of a production system, and the efficiency of resource use. Data Analysis and Synthesis Team (DAST) researchers at OSU continued according to schedule with two studies—one to evaluate and compare two areas of production technology and a second to further refine POND© software. The first study compared fertilization strategies (fixed input versus responsive strategies that were generated by PONDCLASS© pond management software) and feed application rates introduced in Thailand, the Philippines, and Honduras. PONDCLASS© fertilization rates were three to seven times more efficient in terms of phosphorus recovery in fish flesh. The efficiency of nitrogen recovery for responsive strategies was comparable to or slightly higher than fixed input strategies. Fixed input fertilization strategies in general resulted in higher net fish yields; however, treatments receiving responsive fertilization rates were one and a half to three times more cost efficient than fixed input fertilization rates in the Philippines and Thailand and comparable to fixed input rates in Honduras. Results of the comparative analysis showed that fixed input fertilization rates, specifically phosphorus inputs, at CRSP sites could be reduced without compromising production efficiency. To develop feeding schedules that minimize feed use, an adaptive non-linear search strategy implemented in POND© software was used to generate optimal feeding schedules requiring less feed for individual ponds. Simulation results indicated that with minimized feed use culture periods tended to be longer in comparison with satiation feeding. Whether minimum feed use results in net savings requires further analysis; the increased costs of longer culture periods may offset reduced feed costs.

The second research effort of the OSU DAST was directed toward the continued refinement of POND© software and the assessment of PD/A CRSP production technology. To improve the user interface of POND© software and provide increased decision-making support, computer automation tools were implemented to automate processes such as setting up ponds and lots, generating liming and fertilization guidelines, developing optimal feeding schedules, and simplifying the steps required to perform simulations under varied conditions. POND© software models were also upgraded to account for the effects of: 1) fertilization and high fish biomass on fish growth; and 2) the effects of different feed types in terms of moisture, protein, and energy content on fish performance. Additionally, DAST researchers are designing models for POND© software that will simulate phosphorus flux in pond water and sediments and polyculture interactions in ponds.

DAST research at the University of California, Davis (UCD) is progressing according to schedule with the continued improvement of an integrated aquaculture/agriculture model developed from an existing aquaculture pond ecosystem model and modification to several components of a model designed to predict fish growth in stratified fish ponds using stochastic weather variables. Improvements incorporated into the integrated aquaculture/agriculture model included the explicit consideration of organic matter and nitrogen transformations, the incorporation of the effects of low quality feed on fish growth in the fish growth model, the inclusion of sediments in the mass balance equations, and the coupling of an agricultural component to the aquaculture pond ecosystem model. The most recent developments involved incorporating sediment mineral processes, calculating the carbon to nitrogen ratio in the water column, and modeling the light extinction coefficient in ponds with high non-algal turbidity. Data relating to environmental conditions, feed and fertilization rates, and stocking densities from the Butare Rwanda CRSP site were used to run the model, and the three ponds used for model calibration received a weekly input combination of green grass, urea, and chicken manure. Researchers tested the improved accuracy of parameters relating to water column organic matter, water column total ammonia nitrogen, sediment organic matter and sediment total nitrogen, and chlorophyll *a*. Simulated and observed values for chlorophyll *a*, total ammonia nitrogen concentrations in the water column, and sediment organic matter and total nitrogen were comparable. Results of this experiment also indicated that an increased level of computational detail in the water column and sediment processes is necessary to improve the accuracy of simulation of organic matter and nitrogen.

In addition to improving the integrated aquaculture/agriculture model, DAST researchers at UCD further modified several components of a model designed to predict the effects of random weather variables on water temperature, dissolved oxygen, and fish growth in stratified fish ponds. The model is now better able to quantify phytoplankton respiration. It can factor in pond water exchange and assess variables such as different types of organic matter with varying rates of decomposition and oxygen consumption. The fish growth model was also modified to allow for the consumption of different foods. Data from the PD/A CRSP Rwanda site were used to test the model, which was run 20 times for a simulation period of 146 days. Results of simulations indicated a high degree of stratification in the water column of ponds, which may have been due to a high light extinction coefficient and high phytoplankton concentrations. Simulated average fish weight and observed fish weight were in close agreement. Results also showed that the probable range of expected fish size increased as the duration of the growing period increased.

Since its beginning the PD/A CRSP has provided either direct or indirect funding for students seeking undergraduate and graduate level degrees related to the field of aquaculture. Adoption/Diffusion research regarding the human capital impacts attributable to the Global Experiment is delayed. Scientists from Auburn University are initiating an exploratory study to determine: 1) students' motivations for pursuing degrees related to aquaculture; 2) the career path of students since they completed their degrees; 3) the extent of aquaculture information disseminated in students' communities as a result of their education; and 4) the students' contributions to CRSP project goals during their academic careers and after graduation.

Pond Soil Characteristics and Dynamics of Soil Organic Matter and Nutrients

Eighth Work Plan, Pond Dynamics Research 1 (PDR1)

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Introduction

A system to describe pond soil horizons was proposed by Munsiri et al. (1995). This system may be useful for the systematic characterization of pond soil and for soil descriptions used in research projects. It serves as a basis for developing a pond soil classification scheme similar to the system of soil taxonomy used in traditional soil science (Soil Survey Staff, 1975, 1994) and serves as an aid to aquaculture pond management (Boyd, 1995). The proposed system of soil description provides a framework for additional data on pond soil characteristics collected from Pond Dynamics/Aquaculture CRSP prime sites. Data collected within this framework will also be extremely useful to the PD/A CRSP, because it will allow detailed descriptions of soils at the CRSP prime sites in several countries.

This report contains data on soil characteristics for PD/A CRSP ponds in Thailand and Honduras. Additional information will be obtained for ponds at the Kenya CRSP site during 1997.

Methods and Materials

Ponds

Freshwater ponds in this study are located on the campus of the Asian Institute of Technology (AIT), Bangkok, Thailand, and at the El Carao National Fish Culture Center, Comayagua, Honduras. All ponds are used for CRSP research. At AIT, three ponds were 12 years old and three ponds were three years old. These will be referred to as old and new ponds, respectively. The ponds at El Carao were constructed in the early 1980s, but they were extensively renovated in 1990. The three brackish water ponds used in this study are located on the Granjas Marinas San Bernardo shrimp farm near Choluteca, Honduras. The ponds have been in production for 12 years. The shrimp farm allows the CRSP to use the ponds for research.

Ponds at AIT were 500 to 1,000 m^2 with average depths of approximately 100 cm, while ponds at El Carao were 1,000 m^2 with average depths of 80 cm. The brackish water ponds were about 1 ha in size with average depths of 50 to 70 cm.

Sampling

Soil cores were taken with a hand-operated, 5-cm-diameter core sampler (Wildlife Supply Company, Saginaw, Michigan, USA). Procedures for separating the cores into successive 2-cm-long core segments are described by Munsiri et al. (1995). Core segments were dried at 102°C (for analysis of moisture content and dry bulk density) or at 60°C (for other analyses) and transported to Auburn University for analyses.

Physical and Chemical Analyses

Samples were analyzed for moisture content (gravimetry), dry bulk density (gravimetry), color (Munsell color chart), wet soil pH (direct, glass electrode), dry soil pH (1:1 slurry of dry soil and distilled water, glass electrode), exchangeable acidity (Adams-Evans buffer method), particle

Table 1. Profiles for moisture content in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as percentages of dry weight. Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	160.8 ± 7.9	279.2 ± 29.5	217.5 ± 21.9	209.7 ± 27.7
2-4	104.8 ± 1.0	189.6 ± 14.9	136.6 ± 17.0	164.1 ± 32.3
4-6	102.9 ± 5.8	186.3 ± 24.0	89.8 ± 5.3	114.6 ± 14.6
6-8	86.7 ± 9.0	170.3 ± 17.0	66.6 ± 1.5	91.7 ± 7.4
8-10	82.5 ± 10.2	162.5 ± 16.6	57.4 ± 0.7	95.4 ± 12.4
10-12	78.1 ± 9.9	130.7 ± 12.4	54.2 ± 0.8	76.9 ± 2.1
12-14	69.7 ± 8.1	120.0 ± 10.4	48.0 ± 1.9	72.0 ± 1.3
14-16	68.6 ± 7.6	108.5 ± 9.1	45.0 ± 0.9	69.1 ± 3.2
16-18	60.4 ± 4.8	103.1 ± 9.5	36.1 ± 2.1	63.7 ± 4.1
18-20	57.0 ± 5.0	102.8 ± 9.2	32.2 ± 2.1	55.4 ± 2.2
20-22		86.4 ± 5.3	31.3 ± 1.9	51.1 ± 2.6
22-24		74.3 ± 1.5	32.1 ± 1.9	52.4 ± 3.8
24-26		64.8 ± 3.7		51.1 ± 4.9
26-28		60.9 ± 2.9		53.6 ± 5.6
28-30		56.7 ± 2.5		
30-32		49.2 ± 1.8		
32-34		46.5 ± 1.6		
34-36		45.4 ± 2.0		

density (pycnometer method), total carbon and nitrogen (Leco CHN Analyzer), total phosphorus (perchloric acid oxidation), total sulfur (Leco Sulfur Analyzer), and acid-extractable phosphorus, and metal ions (extraction in a 0.075 N acid solution of 0.05 N HCl plus 0.025 N H_2SO_4 followed by plasma spectrophotometry). Details of all analyses are described by Munsiri et al. (1995).

Results and Discussion

A flocculent layer of water with a high concentration of recently-settled solids extended 1 to 3 cm above the soil-water interface in all core samples. This is the F horizon described by Munsiri et al. (1995). The moisture content (Table 1) and the dry bulk density (Table 2) of core segments decreased with depth in cores, and as a result, the dry bulk density of core segments increased (Table 2). The 0-2 cm segment was much lower in dry bulk density than deeper segments. Thus, the S horizon, defined as the layer with a bulk density of 0.3 g cm^{-3} or less (Munsiri et al., 1995) was confined to the upper 2 cm layer. Actually, the new ponds at AIT had an S horizon less than 2 cm in depth, because the 0-2 cm layer had a bulk density greater than 0.3 g cm^{-3}. To delineate the thickness of the S horizon (bulk density less than 0.3 g cm^{-3}) in the new ponds at AIT, thinner core segments were necessary; however in practice it was not possible to cut thinner core segments. Dry bulk density was below 0.7 g cm^{-3} between the following depths in the different ponds: 2 to 6 cm in new ponds at AIT; 2 to 22 cm in old ponds at AIT; 2 to 4 cm in freshwater ponds in Honduras; 2 to 8 cm in brackish water ponds in Honduras. This layer represents the M horizon or the mature, bulk sediment (Munsiri et al., 1995). Munsiri et al. (1995) decided upon a bulk density of 1.4 g cm^{-3} to divide the original pond soil from the sediment. In the present work, the core extended into the original soil in all ponds, but none of the bulk density values reached 1.4 g cm^{-3}. Munsiri et al. (1996a) also reported bulk density values for core segments from ponds at former PD/A CRSP sites in Egypt, and none of them exceeded 1 g cm^{-3}. Thus, many original pond soils do not have bulk densities as high as those found in the ponds at Auburn, Alabama, that were used by Munsiri et al. (1995) to develop the proposed system for separating pond

Table 2. Profiles for dry bulk density in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as grams dry soil solids per cubic centimeter (g cm^{-3}). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.41 ± 0.00	0.29 ± 11.02	0.34 ± 0.04	0.31 ± 0.01
2-4	0.62 ± 0.01	0.41 ± 11.60	0.57 ± 0.08	0.46 ± 0.08
4-6	0.67 ± 0.02	0.41 ± 11.65	0.80 ± 0.04	0.58 ± 0.06
6-8	0.83 ± 0.08	0.44 ± 11.95	0.87 ± 0.02	0.68 ± 0.03
8-10	0.84 ± 0.07	0.45 ± 12.06	0.89 ± 0.03	0.68 ±0.06
10-12	0.87 ± 0.06	0.55 ± 12.31	0.99 ± 0.03	0.71 ± 0.00
12-14	0.84 ± 0.06	0.57 ± 12.52	1.10 ± 0.04	0.79 ± 0.04
14-16	0.94 ± 0.02	0.63 ± 13.03	1.14 ± 0.02	0.88 ± 0.09
16-18	0.96 ± 0.07	0.67 ± 13.25	1.20 ± 0.02	0.98 ± 0.10
18-20	0.95 ± 0.08	0.69 ± 13.35	1.32 ± 0.03	0.89 ± 0.00
20 22		0.73 ± 13.82	1.34 ± 0.04	1.08 ± 0.04
22-24		0.81 ± 14.61	1.31 ± 0.04	1.05 ± 0.06
24-26		0.93 ± 15.26		1.03 ± 0.11
26-28		0.94 ± 15.43		1.03 ± 0.08
28-30		0.96 ± 15.58		
30-32		1.12 ± 16.83		
32-34		1.16 ± 16.97		
34-36		1.14 ± 16.89		

soil profiles into horizons. Clayey soils have lower bulk densities than coarser soils; the soils in Egypt (Munsiri et al., 1996a) and in the present study were more clayey than those at Auburn. This suggests that a lower bulk density value should be used to separate the sediment from the original soil. Based on results obtained in the present study, a bulk density value of 1.0 g cm^{-3} appears to be a suitable division. Use of this value would also be appropriate for soils at Auburn University because it would not result in appreciable differences in depths of the P horizons that were originally delineated by the higher value of 1.4 g cm^{-3}. Thus, the P horizon (original, undisturbed pond soil) occurred below a depth of 16 cm in new ponds at AIT, below 28 cm in old ponds at AIT, below 10 cm in freshwater ponds in Honduras, and below 20 cm in brackish water ponds in Honduras. The T horizon (transitional layer) should now be defined as the layer with a bulk density between 0.8 and 1.0 g cm^{-3}.

Results for ponds at AIT agree with findings of Munsiri et al. (1995) that the sediment layer, and particularly the depth of the M horizon, increases as ponds become older. The S horizon is very fluid and thought to be the layer in which most reactions between soil and water occur. Initial work by Munsiri et al. (1995, 1996a) suggests that the upper 5-cm layer was most reactive with the water, but of the present findings suggest that the most reactive layer may be even thinner in some ponds.

Color values obtained with the Munsell color chart are summarized in Table 3. Colors tended to be darkest in the S and M horizons and lighter in the T and P horizons. The greater concentration of organic matter in the S and M horizons results in a darker color than in the two deeper horizons. Also, the organic matter provides a substrate for microbial activity which drives the redox potential down, and at lower redox potentials, soil color is darker. The color measurement was taken at the mid-point of core segments. The surface layer to a depth of 1 or 2 mm was brown in all 0 to 2 cm core segments, but below this the color was much darker. Thus, the oxidized layer (S_O horizon) was very thin as compared to the S_R horizon (reduced part of the S horizon). Munsiri et al. (1995) reported that the S_O horizon in pond soil profiles at Auburn also was only a few millimeters thick.

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Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.41 ± 0.00	0.29 ± 11.02	0.34 ± 0.04	0.31 ± 0.01
2-4	0.62 ± 0.01	0.41 ± 11.60	0.57 ± 0.08	0.46 ± 0.08
4-6	0.67 ± 0.02	0.41 ± 11.65	0.80 ± 0.04	0.58 ± 0.06
6-8	0.83 ± 0.08	0.44 ± 11.95	0.87 ± 0.02	0.68 ± 0.03
8-10	0.84 ± 0.07	0.45 ± 12.06	0.89 ± 0.03	0.68 ±0.06
10-12	0.87 ± 0.06	0.55 ± 12.31	0.99 ± 0.03	0.71 ± 0.00
12-14	0.84 ± 0.06	0.57 ± 12.52	1.10 ± 0.04	0.79 ± 0.04
14-16	0.94 ± 0.02	0.63 ± 13.03	1.14 ± 0.02	0.88 ± 0.09
16-18	0.96 ± 0.07	0.67 ± 13.25	1.20 ± 0.02	0.98 ± 0.10
18-20	0.95 ± 0.08	0.69 ± 13.35	1.32 ± 0.03	0.89 ± 0.00
20 22		0.73 ± 13.82	1.34 ± 0.04	1.08 ± 0.04
22-24		0.81 ± 14.61	1.31 ± 0.04	1.05 ± 0.06
24-26		0.93 ± 15.26		1.03 ± 0.11
26-28		0.94 ± 15.43		1.03 ± 0.08
28-30		0.96 ± 15.58		
30-32		1.12 ± 16.83		
32-34		1.16 ± 16.97		
34-36		1.14 ± 16.89		

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Table 4. Profiles for wet soil pH by direct measurement in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as standard pH units. Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	7.65 ± 0.19	7.28 ± 0.03	7.28 ± 0.06	7.28 ± 0.06
2-4	7.35 ± 0.09	7.30 ± 0.07	7.48 ± 0.06	7.48 ± 0.06
4-6	7.17 ± 0.12	7.32 ± 0.02	7.47 ± 0.08	7.47 ± 0.06
6-8	7.27 ± 0.07	7.31 ± 0.04	7.49 ± 0.13	7.49 ± 0.13
8-10	7.35 ± 0.05	7.34 ± 0.01	7.54 ± 0.19	7.54 ± 0.19
10-12	7.37 ± 0.05	7.31 ± 0.02	7.44 ± 0.24	7.44 ± 0.24
12-14	7.27 ± 0.02	7.44 ± 0.01	7.51 ± 0.21	7.51 ± 0.21
14-16	7.19 ± 0.04	7.49 ± 0.05	7.67 ± 0.24	7.67 ± 0.24
16-18	7.12 ± 0.06	7.46 ± 0.04	7.76 ± 0.30	7.76 ± 0.30
18-20		7.43 ± 0.04	7.92 ± 0.18	7.92 ± 0.18
20-22		7.40 ± 0.04	8.16 ± 0.20	8.16 ± 0.20
22-24		7.33 ± 0.02	8.40 ± 0.19	8.40 ± 0.19
24-26		7.25 ± 0.03		
26-28		7.04 ± 0.09		
28-30		6.88 ± 0.08		
30-32		6.32 ± 0.16		
32-34		5.51 ± 0.29		
34-36		5.30 ± 0.14		

Table 5. Profiles for dry soil pH measured in 1:1 slurries of dry soil and distilled water in soil cores of aquaculture ponds. Averages and standard errors are given as standard pH units. Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	6.37 ± 0.04	6.32 ± 0.05	7.15 ± 0.02	6.92 ± 0.12
2-4	6.05 ± 0.06	6.23 ± 0.05	7.07 ± 0.03	6.72 ± 0.06
4-6	6.55 ± 0.15	6.20 ± 0.06	7.10 ± 0.02	6.73 ± 0.04
6-8	6.43 ± 0.15	6.13 ± 0.04	7.10 ± 0.10	6.67 ± 0.02
8-10	6.30 ± 0.08	6.05 ± 0.04	7.15 ± 0.17	6.70 ± 0.02
10-12	6.23 ± 0.13	6.00 ± 0.02	6.95 ± 0.14	6.85 ± 0.03
12-14	6.17 ± 0.14	6.15 ± 0.09	6.92 ± 0.15	6.92 ± 0.05
14-16	5.90 ± 0.29	6.15 ± 0.08	7.35 ± 0.17	6.87 ± 0.08
16-18	5.52 ± 0.47	6.10 ± 0.07	7.45 ± 0.09	6.73 ± 0.08
18-20	5.22 ± 0.52	6.03 ± 0.07	7.87 ± 0.15	6.87 ± 0.07
20-22		6.07 ± 0.13	7.67 ± 0.09	6.68 ± 0.11
22-24		5.93 ± 0.14	7.45 ± 0.15	6.70 ± 0.14
24-26		5.60 ± 0.22		
26-28		5.28 ± 0.15		
28-30		5.75 ± 0.64		
30-32		4.10 ± 0.20		
32-34		3.38 ± 0.05		
34-36		3.13 ± 0.05		

Table 6. Profiles for exchangeable acidity in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as milliequivalents per 100 grams dry soil (meq 100 g^{-1}). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	3.47 ± 0.31	4.53 ± 0.43	1.73 ± 0.08	1.33 ± 0.20
2-4	5.87 ± 0.31	4.80 ± 0.23	2.00 ± 0.13	0.93 ± 0.08
4-6	4.00 ± 0.13	4.80 ± 0.27	2.00 ± 0.13	1.33 ± 0.08
6-8	4.53 ± 0.15	5.07 ± 0.28	1.87 ± 0.08	1.33 ± 0.08
8-10	4.67 ± 0.28	5.60 ± 0.27	1.87 ± 0.15	1.47 ± 0.28
10-12	4.80 ± 0.35	5.73 ± 0.08	1.87 ± 0.15	1.20 ± 0.00
12-14	5.07 ± 0.28	5.20 ± 0.23	1.60 ± 0.00	0.93 ± 0.08
14-16	5.60 ± 0.58	5.33 ± 0.08	1.87 ± 0.08	0.93 ± 0.08
16-18	4.40 ± 0.35	5.33 ± 0.15	1.33 ± 0.08	0.67 ± 0.08
18-20	4.67 ± 0.28	5.60 ± 0.00	1.47 ± 0.15	1.07 ± 0.08
20-22		5.60 ± 0.00	1.20 ± 0.13	0.93 ± 0.08
22-24		5.87 ± 0.20	1.07 ± 0.15	0.67 ± 0.08
24-26		5.87 ± 0.41		
26-28		6.40 ± 0.23		
28-30		7.33 ± 0.28		
30-32		6.27 ± 0.50		
32-34		6.13 ± 0.20		
34-36		5.87 ± 0.31		

Table 7. Profiles for total carbon in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as percentages. Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	1.82 ± 0.24	2.28 ± 0.05	2.35 ± 0.06	1.77 ± 0.16
2-4	1.63 ± 0.29	2.13 ± 0.05	1.56 ± 0.33	1.68 ± 0.07
4-6	1.82 ± 0.18	2.03 ± 0.02	2.08 ± 0.14	1.80 ± 0.03
6-8	1.46 ± 0.10	1.88 ± 0.06	2.08 ± 0.13	1.72 ± 0.08
8-10	0.88 ± 0.16	1.80 ± 0.05	1.98 ± 0.07	1.40 ± 0.03
10-12	1.17 ± 0.04	1.75 ± 0.04	2.05 ± 0.08	1.35 ± 0.06
12-14	1.15 ± 0.04	1.39 ± 0.11	1.19 ± 0.22	1.14 ± 0.04
14-16	0.72 ± 0.20	1.83 ± 0.08	1.70 ± 0.09	1.20 ± 0.08
16-18	0.98 ± 0.11	1.62 ± 0.01	1.34 ± 0.02	1.15 ± 0.10
18-20	0.67 ± 0.08	1.47 ± 0.06	1.39 ± 0.06	0.96 ± 0.15
20-22		1.69 ± 0.09	1.14 ± 0.20	0.75 ± 0.09
22-24		1.29 ± 0.11	1.33 ± 0.23	0.63 ± 0.06
24-26		1.14 ± 0.15		
26-28		1.71 ± 0.45		
28-30		0.83 ± 0.09		
30-32		0.83 ± 0.12		
32-34		0.54 ± 0.05		
34-36		0.50 ± 0.02		

Table 8. Profiles for total nitrogen in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given in percentages. Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.12 ± 0.02	0.17 ± 0.39	0.29 ± 0.01	0.23 ± 0.02
2-4	0.13 ± 0.01	0.15 ± 0.38	0.19 ± 0.03	0.24 ± 0.00
4-6	0.10 ± 0.01	0.15 ± 0.36	0.25 ± 0.01	0.23 ± 0.01
6-8	0.11 ± 0.00	0.13 ± 0.34	0.24 ± 0.00	0.20 ± 0.01
8-10	0.06 ± 0.01	0.13 ± 0.33	0.23 ± 0.01	0.17 ± 0.01
10-12	0.09 ± 0.00	0.13 ± 0.33	0.21 ± 0.02	0.17 ± 0.01
12-14	0.08 ± 0.01	0.10 ± 0.29	0.15 ± 0.03	0.14 ± 0.01
14-16	0.04 ± 0.01	0.14 ± 0.35	0.20 ± 0.01	0.14 ± 0.01
16-18	0.06 ± 0.01	0.13 ± 0.28	0.15 ± 0.01	0.13 ± 0.01
18-20	0.05 ± 0.00	0.11 ± 0.25	0.12 ± 0.01	0.11 ± 0.02
20-22		0.12 ± 0.31	0.08 ± 0.01	0.10 ± 0.01
22-24		0.06 ± 0.21	0.09 ± 0.01	0.08 ± 0.01
24-26		0.09 ± 0.16		
26-28		0.08 ± 0.55		
28-30		0.06 ± 0.12		
30-32		0.05 ± 0.19		
32-34		0.04 ± 0.09		
34-36		0.04 ± 0.08		

Auburn (Munsiri et al. 1995). Values at Auburn seldom exceeded 7.5:1. The reason for the difference is not known, but it may be related to the fact that ponds at Auburn had received large applications of high-protein fish feed over the years while the CRSP ponds have not received large applications of feed. Ponds at AIT and freshwater ponds in Honduras have been fertilized and manured heavily, while brackish water ponds in Honduras have had quite low nutrient inputs, because they have been managed as extensive shrimp production ponds.

Total phosphorus concentrations in ponds at AIT tended to be greater in S and P horizons than in T and P horizons (Table 9). Dilute acid-extractable phosphorus concentrations were lower in P horizons of old ponds at AIT than in S, M, and T horizons, but differences in acid-extractable phosphorus with depth were not obvious in new ponds (Table 10). The total phosphorus concentrations in ponds in Honduras did not differ with soil depth (Table 9), but in the freshwater ponds, acid-extractable concentrations were much greater in the upper soil layers than in the P horizon (Table 10). Results suggest that phosphorus inputs in fertilizer have raised phosphorus concentrations in the old ponds at AIT and in the freshwater ponds in Honduras. However, increases in phosphorus are not obvious in the other ponds.

New ponds at AIT had similar concentrations of sulfur at all depths, but in old ponds at AIT, core segments from depths of 28 cm or more had a higher concentration of sulfur than segments taken from depths of less than 28 cm (Table 11). Sulfur concentrations above 0.75% suggest that soils are potentially acid-sulfate in nature (Boyd, 1995). There is a layer of acid-sulfate soils below the old ponds at AIT. The freshwater ponds in Honduras had unexpectedly high sulfur concentrations and some core segments can be classified as potential acid-sulfate soil material. However, the soil does not have a low pH when dried. This suggests that there is enough natural base, probably calcium carbonate, in the soil to neutralize acidity created by pyrite oxidation. These samples will be analyzed again to verify the sulfur determination. The deeper samples from the brackish water ponds in Honduras contained less sulfur than the upper soil layers.

Table 9. Profiles for total phosphorus in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given in percentages. Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.10 ± 0.01	0.09 ± 0.01	0.09 ± 0.01	0.08 ± 0.00
2-4	0.06 ± 0.01	0.11 ± 0.00	0.10 ± 0.01	0.09 ± 0.00
4-6	0.08 ± 0.01	0.12 ± 0.00	0.09 ± 0.01	0.11 ± 0.00
6-8	0.17 ± 0.06	0.11 ± 0.01	0.10 ± 0.01	0.11 ± 0.01
8-10	0.04 ± 0.00	0.11 ± 0.00	0.09 ± 0.01	0.10 ± 0.00
10-12	0.04 ± 0.01	0.10 ± 0.01	0.12 ± 0.02	0.10 ± 0.00
12-14	0.04 ± 0.01	0.10 ± 0.01	0.09 ± 0.02	0.10 ± 0.00
14-16	0.03 ± 0.01	0.15 ± 0.01	0.13 ± 0.03	0.10 ± 0.00
16-18	0.02 ± 0.00	0.07 ± 0.01	0.12 ± 0.02	0.09 ± 0.01
18-20	0.05 ± 0.02	0.11 ± 0.01	0.09 ± 0.02	0.09 ± 0.00
20-22		0.09 ± 0.01	0.10 ± 0.02	0.09 ± 0.00
22-24		0.10 ± 0.02	0.09 ± 0.01	0.08 ± 0.01
24-26		0.07 ± 0.01		
26-28		0.06 ± 0.00		
28-30		0.05 ± 0.00		
30-32		0.02 ± 0.01		
32-34		0.02 ± 0.00		
34-36		0.02 ± 0.00		

Table 10. Profiles for dilute acid extractable phosphorus in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	4.77 ± 0.43	10.24 ± 0.88	153.87 ± 17.96	11.74 ± 1.93
2-4	4.58 ± 0.41	11.63 ± 0.78	169.73 ± 27.39	10.17 ± 1.27
4-6	3.76 ± 0.67	11.98 ± 0.95	185.00 ± 19.87	12.20 ± 0.88
6-8	3.94 ± 0.59	13.21 ± 1.48	198.94 ± 38.87	11.82 ± 0.75
8-10	3.03 ± 0.39	13.99 ± 2.35	175.30 ± 28.27	10.32 ± 1.33
10-12	2.60 ± 0.18	16.73 ± 4.1	181.70 ± 43.84	11.15 ± 1.69
12-14	2.95 ± 0.28	16.08 ± 3.97	179.62 ± 50.22	9.42 ± 0.74
14-16	5.31 ± 0.55	18.32 ± 3.99	163.73 ± 70.62	11.25 ± 2.34
16-18	4.07 ± 0.86	16.36 ± 3.90	56.57 ± 22.93	11.04 ± 2.37
18-20	5.02 ± 0.53	13.24 ± 2.65	37.12 ± 14.26	12.70 ± 2.23
20-22		13.56 ± 2.02	25.19 ± 8.09	22.09 ± 1.48
22-24		13.50 ± 0.91	18.43 ± 8.63	21.21 ± 1.75
24-26		14.82 ± 1.34		
26-28		14.06 ± 1.16		
28-30		12.02 ± 2.56		
30-32		9.51 ± 1.53		
32-34		6.18 ± 0.45		
34-36		5.53 ± 0.54		

Table 11. Profiles for total sulfur in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.57 ± 0.13	0.86 ± 0.13	0.79 ± 0.16	0.58 ± 0.06
2-4	0.49 ± 0.08	0.76 ± 0.11	1.08 ± 0.11	0.50 ± 0.12
4-6	0.49 ± 0.05	0.90 ± 0.15	0.89 ± 0.08	0.66 ± 0.10
6-8	0.45 ± 0.06	0.85 ± 0.14	1.02 ± 0.12	0.67 ± 0.07
8-10	0.46 ± 0.08	0.83 ± 0.13	0.70 ± 0.06	0.70 ± 0.06
10-12	0.37 ± 0.09	0.70 ± 0.10	3.39 ± 1.57	0.64 ± 0.04
12-14	0.44 ± 0.08	0.65 ± 0.07	3.42 ± 1.63	0.73 ± 0.07
14-16	0.42 ± 0.09	0.70 ± 0.04	0.48 ± 0.05	0.61 ± 0.06
16-18	0.34 ± 0.04	0.73 ± 0.01	0.43 ± 0.05	0.35 ± 0.07
18-20	0.33 ± 0.07	0.77 ± 0.05	0.31 ± 0.07	0.43 ± 0.08
20-22		0.83 ± 0.06	0.52 ± 0.07	0.28 ± 0.05
22-24		0.81 ± 0.06	0.49 ± 0.04	0.15 ± 0.01
24-26		0.60 ± 0.04		
26-28		0.73 ± 0.14		
28-30		1.01 ± 0.21		
30-32		1.40 ± 0.18		
32-34		1.55 ± 0.18		
34-36		1.88 ± 0.21		

We suspect that iron pyrite is actively being formed in these ponds. Earlier work on pond soil at Granjas Marinas (Munsiri et al., 1996b) showed that surface layers of soil in old ponds had more sulfur than those in newer ponds. This observation also suggests active pyrite formation.

Large inputs of calcium to ponds at AIT in liming materials resulted in greater calcium concentrations in upper soil layers than in deeper ones (Table 12). Soil at the freshwater site in Honduras is naturally high in calcium, and core segments from all depths were high in calcium. Calcium concentrations were much lower in the brackish water ponds in Honduras than in the freshwater ponds. The native soils in the area of the shrimp farm are acidic, and therefore, low in calcium. Liming has not been a normal practice on the farm, and brackish water has a rather low proportion of calcium in relation to other basic cations (Boyd, 1990).

The upper soil layers at AIT were enriched with magnesium, suggesting that the liming materials used there contained magnesium (Table 13). Little difference in magnesium concentration occurred with depth in the freshwater ponds in Honduras. Magnesium has accumulated in the surface layers of soil in the brackish water ponds in Honduras (Table 13). This has resulted from the high concentrations of magnesium in brackish water.

The deeper layers of soil in all freshwater ponds tended to contain less potassium and sodium than upper layers, and there was an obvious accumulation of these two ions in surface layers of brackish water ponds (Tables 14 and 15). Accumulation of sodium and potassium in the upper layers of brackish water ponds obviously resulted from inputs of these ions in salt water. Reasons for the increases in the freshwater ponds cannot be determined from available data.

Concentrations of iron, manganese, zinc, and copper are provided in Tables 16 through 19. Values for iron varied somewhat with depth, but obvious patterns were not found. Pond soils in Thailand contained much higher iron concentrations than those in Honduras. Manganese tended to accumulate in upper soil layers, but the reason for this process is not known. Brackish water pond soils contained greater manganese concentrations than freshwater ones. Zinc concentrations were much greater in freshwater pond soils than in brackish water ones. In freshwater pond soils,

Table 12. Profiles for calcium in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	4971 ± 217	3580 ± 263	5849 ± 887	844 ± 69
2-4	4687 ± 187	3091 ± 209	5738 ± 704	721 ± 80
4-6	5040 ± 147	3148 ± 238	6290 ± 1044	681 ± 10
6-8	5325 ± 314	3032 ± 97	5949 ± 825	600 ± 28
8-10	5187 ± 171	3018 ± 97	5827 ± 671	723 ± 70
10-12	5105 ± 124	3258 ± 174	5789 ± 749	597 ± 20
12-14	4666 ± 131	3493 ± 49	5709 ± 733	700 ± 59
14-16	4094 ± 322	3328 ± 137	6052 ± 816	817 ± 75
16-18	4033 ± 290	3712 ± 104	6933 ± 1353	526 ± 23
18-20	3404 ± 374	3659 ± 130	7088 ± 1418	620 ± 148
20-22		3678 ± 165	7326 ± 1481	434 ± 29
22-24		3270 ± 271	5617 ± 2074	445 ± 60
24-26		2857 ± 360		
26-28		2606 ± 263		
28-30		2503 ± 439		
30-32		2195 ± 486		
32-34		1708 ± 440		
34-36		1810 ± 542		

Table 13. Profiles for magnesium in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	645 ± 20	771 ± 39	460 ± 93	1517 ± 101
2-4	516 ± 22	751 ± 20	421 ± 103	1274 ± 91
4-6	511 ± 19	744 ± 26	402 ± 86	1173 ± 49
6-8	531 ± 14	726 ± 24	402 ± 85	1065 ± 49
8-10	498 ± 27	699 ± 15	423 ± 121	1091 ± 56
10-12	473 ± 5	694 ± 12	416 ± 73	1019 ± 22
12-14	434 ± 13	685 ± 24	448 ± 100	964 ± 32
14-16	422 ± 9	670 ± 23	366 ± 86	866 ± 15
16-18	419 ± 11	655 ± 13	367 ± 72	955 ± 26
18-20	402 ± 4	614 ± 18	331 ± 71	899 ± 55
20-22		583 ± 9	355 ± 55	894 ± 39
22-24		556 ± 20	305 ± 109	852 ± 56
24-26		503 ± 23		
26-28		473 ± 8		
28-30		475 ± 13		
30-32		418 ± 16		
32-34		342 ± 36		
34-36		327 ± 39		

Table 14. Profiles for potassium in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	176 ± 8	240 ± 14	463 ± 94	582 ± 48
2-4	201 ± 20	234 ± 13	456 ± 103	473 ± 52
4-6	175 ± 13	236 ± 13	458 ± 98	426 ± 33
6-8	232 ± 34	241 ± 12	458 ± 100	389 ± 19
8-10	170 ± 14	239 ± 13	456 ± 101	406 ± 19
10-12	160 ± 14	244 ± 12	472 ± 93	388 ± 6
12-14	154 ± 13	241 ± 19	466 ± 98	388 ± 13
14-16	150 ± 8	259 ± 21	442 ± 96	357 ± 3
16-18	146 ± 6	269 ± 15	412 ± 70	360 ± 13
18-20	134 ± 1	258 ± 25	366 ± 61	323 ± 15
20-22		259 ± 25	361 ± 55	298 ± 2
22-24		273 ± 29	291 ± 97	265 ± 7
24-26		265 ± 26		
26-28		266 ± 29		
28-30		265 ± 28		
30-32		227 ± 24		
32-34		358 ± 117		
34-36		159 ± 26		

Table 15. Profiles for sodium in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	455 ± 4	629 ± 52	729 ± 38	10179 ± 957
2-4	418 ± 21	507 ± 35	642 ± 133	7475 ± 919
4-6	405 ± 10	470 ± 34	537 ± 51	6567 ± 474
6-8	424 ± 15	428 ± 23	609 ± 83	5498 ± 408
8-10	366 ± 8	380 ± 15	588 ± 163	5697 ± 349
10-12	326 ± 10	369 ± 18	792 ± 89	4947 ± 232
12-14	291 ± 12	366 ± 19	874 ± 163	4754 ± 232
14-16	274 ± 4	352 ± 15	464 ± 41	4420 ± 199
16-18	284 ± 2	363 ± 10	668 ± 160	4389 ± 196
18-20	262 ± 7	336 ± 14	447 ± 28	4178 ± 238
20-22		328 ± 6	777 ± 110	4042 ± 307
22-24		313 ± 9	712 ± 208	3926 ± 465
24-26		292 ± 6		
26-28		281 ± 6		
28-30		293 ± 9		
30-32		262 ± 10		
32-34		228 ± 26		
34-36		212 ± 26		

Table 16. Profiles for iron in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	128 ± 38	269 ± 63	17 ± 5	24 ± 3
2-4	148 ± 47	359 ± 45	22 ± 8	33 ± 10
4-6	135 ± 41	364 ± 52	15 ± 4	23 ± 8
6-8	129 ± 36	355 ± 46	19 ± 7	18 ± 8
8-10	121 ± 30	320 ± 31	15 ± 5	12 ± 7
10-12	126 ± 21	293 ± 19	14 ± 5	14 ± 3
12-14	123 ± 33	276 ± 52	14 ± 5	8 ± 2
14-16	157 ± 31	346 ± 61	12 ± 4	2 ± 1
16-18	202 ± 22	283 ± 33	7 ± 2	5 ± 0
18-20	213 ± 17	187 ± 43	5 ± 1	2 ± 1
20-22		312 ± 29	5 ± 0	4 ± 2
22-24		379 ± 52	5 ± 1	14 ± 7
24-26		350 ± 63		
26-28		334 ± 28		
28-30		322 ± 15		
30-32		233 ± 14		
32-34		184 ± 17		
34-36		198 ± 15		

Table 17. Profiles for manganese in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	26 ± 2	72 ± 11	167 ± 55	282 ± 24
2-4	23 ± 1	66 ± 7	157 ± 56	234 ± 16
4-6	23 ± 2	65 ± 6	148 ± 48	206 ± 20
6-8	23 ± 1	62 ± 5	126 ± 50	183 ± 12
8-10	24 ± 1	58 ± 2	108 ± 46	183 ± 26
10-12	23 ± 3	59 ± 3	90 ± 31	213 ± 15
12-14	20 ± 4	63 ± 5	90 ± 34	194 ± 17
14-16	20 ± 3	63 ± 6	69 ± 33	171 ± 19
16-18	20 ± 3	63 ± 8	41 ± 18	168 ± 8
18-20	19 ± 3	58 ± 7	19 ± 9	131 ± 6
20-22		58 ± 9	10 ± 3	129 ± 24
22-24		51 ± 8	8 ± 3	78 ± 2
24-26		43 ± 9		
26-28		35 ± 6		
28-30		31 ± 4		
30-32		25 ± 3		
32-34		19 ± 1		
34-36		17 ± 1		

Table 18. Profiles for zinc in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	9.98 ± 5.60	10.22 ± 2.56	4.28 ± 2.02	0.40 ± 0.12
2-4	4.46 ± 1.28	14.05 ± 1.48	4.85 ± 2.61	0.94 ± 0.12
4-6	21.86 ± 10.60	16.45 ± 0.97	4.25 ± 2.03	1.03 ± 0.08
6-8	12.96 ± 6.57	19.27 ± 0.45	5.32 ± 2.89	1.11 ± 0.16
8-10	19.56 ± 10.28	19.69 ± 1.57	4.90 ± 2.71	0.85 ± 0.08
10-12	12.88 ± 5.90	16.72 ± 0.86	4.34 ± 2.38	0.79 ± 0.04
12-14	3.87 ± 0.99	13.81 ± 1.59	3.54 ± 1.84	0.62 ± 0.04
14-16	8.99 ± 2.40	15.25 ± 0.89	2.51 ± 1.45	0.45 ± 0.14
16-18	3.88 ± 0.36	15.25 ± 0.64	0.47 ± 0.27	0.72 ± 0.08
18-20	3.53 ± 0.64	12.08 ± 0.64	0.00 ± 0.00	0.44 ± 0.13
20-22		10.09 ± 0.84	0.00 ± 0.00	0.87 ± 0.05
22-24		6.48 ± 1.62	0.00 ± 0.00	0.70 ± 0.05
24-26		11.91 ± 2.23		
26-28		11.75 ± 1.59		
28-30		8.53 ± 1.18		
30-32		3.87 ± 0.25		
32-34		1.88 ± 0.37		
34-36		1.81 ± 0.07		

Table 19. Profiles for copper in soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	**Thailand**		**Honduras**	
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackish water ponds*
0-2	0.06 ± 0.02	0.55 ± 0.29	0.67 ± 0.18	0.00 ± 0.00
2-4	0.25 ± 0.07	0.43 ± 0.25	0.70 ± 0.31	0.00 ± 0.00
4-6	0.04 ± 0.01	0.47 ± 0.15	0.41 ± 0.14	0.00 ± 0.00
6-8	0.15 ± 0.08	0.28 ± 0.10	0.58 ± 0.33	0.00 ± 0.00
8-10	0.00 ± 0.00	0.47 ± 0.20	0.43 ± 0.25	0.00 ± 0.00
10-12	0.00 ± 0.00	0.39 ± 0.15	0.40 ± 0.23	0.00 ± 0.00
12-14	0.46 ± 0.15	0.05 ± 0.03	0.43 ± 0.25	0.00 ± 0.00
14-16	1.10 ± 0.24	0.01 ± 0.01	0.29 ± 0.17	0.00 ± 0.00
16-18	0.89 ± 0.29	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
18-20	0.82 ± 0.21	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
20-22		0.19 ± 0.11	0.00 ± 0.00	0.00 ± 0.00
22-24		0.49 ± 0.15	0.00 ± 0.00	0.37 ± 0.21
24-26		0.98 ± 0.31		
26-28		1.13 ± 0.22		
28-30		1.64 ± 0.15		
30-32		1.41 ± 0.18		
32-34		1.06 ± 0.05		
34-36		3.47 ± 1.43		

zinc concentrations were higher in upper layers than in deeper ones, but this trend was not obvious in brackish water pond soils. Copper concentrations were very low in soils of all ponds.

Only the upper 5 to 10 cm of pond bottom soil influences water quality in ponds (Boyd, 1995), so from a management standpoint, the composition of this surface layer is of most importance. Nevertheless, the characteristics of the soil profile can be of interest in classifying pond soils, determining the effects of aquaculture on the pond bottom soil, and providing clues to chemical processes in pond soils. Boyd et al. (1994) made chemical analyses of soil samples (upper 5-cm layer) from over 300 brackish water ponds and more than 300 freshwater ponds from several nations. Arrays made from the data permitted classification of samples as very low, low, high, and very high in concentrations of each variable. Nearly all of the data for 0-2 cm and 2-4 cm core segments in the present study were medium with respect to chemical properties.

Data collected in this study show that the proposed system for delineating pond soil horizons suggested by Munsiri et al (1995) can be applied to pond soils at a diversity of sites. The patterns of change in soil properties with depth that were noted in this study were similar to those found in ponds at Auburn (Munsiri et al., 1995).

Brackish water ponds had much higher concentrations of sodium, potassium, and magnesium in surface layers than did freshwater ponds because of large inputs of these ions in brackish water. There were some differences in soil properties among sites that were related to the native characteristics of site soils, and some changes in soils could be associated with aquacultural operations. Once soil profile data are obtained from further sites, it will be possible to develop a system of pond soil taxonomy based on physical and chemical properties.

Anticipated Benefits

This research will provide valuable information on pond soils at the prime sites that can be used by PD/A CRSP investigators for describing bottom soils of ponds in research papers, in designing experiments, and in evaluating experiment results. The data also provide further verification that the method of delineating pond soil horizons suggested by Prasert Munsiri, C.E. Boyd, and B.F. Hajek of Auburn University is applicable to a diversity of sites. The findings enhance our knowledge of chemical characteristics of soil profiles that can be used to develop a system of pond soil taxonomy similar to the system of soil taxonomy used in traditional soil science. The physical and chemical changes in soil profiles will also be useful in making inferences about the influence of pond management on pond bottom soils. Knowledge of soil properties also aids pond management decisions regarding inputs that are needed to improve environmental quality within culture systems.

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Artificial Propagation of Nile Tilapia for Chromosome Manipulation

Eighth Work Plan, Reproduction Control Research 1B (RCR1B)

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Introduction

Manipulation of fish reproduction, an important scientific development for aquaculture, may be performed at various levels of artificial propagation. Spawning may be controlled through environmental manipulation or through direct hormonal intervention (Shelton, 1989). The basic techniques and capacity for control vary between species. Tilapias do not respond well to hormonal induction but can be induced to spawn through manipulation of environmental variables. A suitable temperature and controlled photoperiod permit a reasonably close prediction of ovulation time.

Chromosome manipulation, which includes ploidy alteration or euploidy induction with single parent genome contribution, requires the collection of freshly released gametes. Ploidy manipulation includes the induction of triploids through polar body retention or tetraploidy through interference with first karyokinesis. Euploid alterations include gynogenetic (gynogenote) diploidization of the maternal genome through polar body retention (meiogynote) or mitotic interference (mitogynote). Diploidization of the paternal genome (androgenote), or androgenesis, is accomplished by interference with first mitosis. In the case of androgenesis and gynogenesis, either the female or male DNA, respectively, must be rendered inactive before the egg is activated. Both parental genomes are intact, however, during ploidy manipulation. This report describes initial efforts in the collection of freshly ovulated eggs from Nile tilapia (*Oreochromis niloticus*) for use in experiments to develop techniques for induction of androgenotes.

Chromosome manipulation involves one or two basic treatments of freshly obtained gametes (Thorgaard and Allen, 1986). For gynogenesis or androgenesis the first treatment is the genome deactivation of the spermatozoa or eggs, respectively. Ultraviolet irradiation is preferred for simplicity and safety, but also because it dimerizes the DNA rather than fragmenting it. Activation of treated spermatozoa or eggs requires diploidization by some form of shock that either retains the second polar body (pb) or interrupts the first mitotic karyokinesis. Shock is most often physical (e.g., thermal [cold or hot] or pressure). Thermal treatment is usually preferred because of the ease of application and the simplicity of the equipment used. To disrupt chromosome separation the shock must coincide with metaphase and be sufficiently severe to disrupt the spindle fibers. Thus, shock intensity, duration, and time of application must be optimally combined to ensure a maximum yield of progeny. Further, because the rate of development is inversely temperature dependent, either the preshock incubation temperature must be standardized or the shock time must be calibrated to compensate for the temperature effect. Absolute shock time (τ_S, in minutes post-activation) can be related to tau (τ_0, in minutes) to report shock protocol in a dimensionless term (τ_S/τ_0) which is temperature compensated (Dettlaff and Dettlaff, 196l; Dettlaff 1986).

The development of a tau curve over the spawning temperature range of Nile tilapia was one of the initial segments of Reproduction Control Research 1 in the Eighth Work Plan.

Methods and Materials

Spawning

This study used the University of Oklahoma stock of *O. niloticus*, obtained from Auburn University, originated in the Ivory Coast, and hybridized to an unknown level with the Egyptian Lake Manzala stock carrying the blond gene (McAndrew et al., 1988). Spawning was managed by photoperiod manipulation. Four to six females were stocked with one male in four 550-l aquaria. Water was aerated and circulated at the rate of one turnover per day and temperature was maintained at 26 ± 2˚C. The light cycle was initiated at 0100 h; the time of sunset signaled the end of the photoperiod for a total of about 20 light hours and 4 dark hours (20L:4D). Tilapia spawn about 8 to 10 h after the beginning of the light cycle (Myers and Hershberger, 1991). Ovulation and spawning readiness were determined through observation of courtship behavior, coloration, and papilla erection (Rothbard and Pruginin, 1975; Rothbard, 1979). Females were stripped after the initiation of spawning or upon observation of other determinants.

Fertilization

Eggs were collected in a clean container, milt was expressed over the eggs, and water was directly added to initiate activation. Within two to three minutes of activation fertilized eggs were placed in controlled temperature (± 0.2˚C) incubators. The incubation temperature was closely regulated to document the embryonic rate of development, so that timing of diploidization shock could be determined. Eggs were incubated in 1-l upwelling units with sufficient flow to gently tumble the developing embryos.

Tau Estimates

Developmental rate is defined as the duration of one mitotic cycle during early synchronous cleavage (Dettlaff and Dettlaff, 1961). The mean interval between the initiation of the first and third mitoses in 5 to 10% of the eggs was recorded at temperatures within the usual developmental range (20 to 30˚C). Twenty to thirty eggs were examined under magnification at five-minute intervals. Tau curves have been used to facilitate chromosome manipulation studies in various fishes (Shelton and Rothbard, 1993; Shelton et al., 1997). The mechanics of this technique have been more difficult with tilapias due to the difficulties associated with gamete collection.

Results

Photoperiod manipulation induced spawning activity to occur at midday. Females ovulated/ spawned between 9.5 and 13.5 h (mean = 10.1 h) after initiation of the light cycle. There was no apparent correlation between the latent period and water temperature; however, temperature variation was low (23.9 to 27.7˚C). During the spring 1997 spawning season, eggs were collected from ten Nile tilapia.

Fertilization rates were variable with no development in five of ten batches. Fertilization and hatching rates are poor among tilapias even though egg resorption is common. Egg resorption does not always prevent ovulation of the bad eggs (Peters, 1983). The low rate of fertilization may also be due to the type of incubation system used. The hatch rate of an upwelling type of incubator is not as good as a down-flow system incubator (Rana, 1986). We are in the process of modifying our incubators.

Estimates of tau were made at five temperatures ranging from 20.6 to 27.5˚C (Table 1). The sample size of this study is too small to evaluate variability, however, the estimates of variability have been tightly associated with a tau curve calculated from data on time to first mitosis in *O. aureus* (Don, 1989). The theoretical tau curve for Nile tilapia used in

Table 1. Temperature-tau relationship for Nile tilapia.

Incubation Temperature (˚C)	**Observed τ_0** (minutes)	**Calculated τ_0** (minutes)[1]
20.6	73.5	72.0
21.6	67.5	65.0
22.4	56.5	59.0
24.7	50.0	47.0
27.5	30.0	36.0

[1] Calculated curve developed from data for time to first mitoses in *O. aureus* (Don, 1989) based on methods of Rubenshtein et al. (1997); the calculated tau curve is characterized by the relationship: $\tau_0 = 10^5 x^{-2.39}$ where x = temperature (˚C).

this study was generated using the techniques of Rubinshtein et al. (1997). This curve is characterized by the relationship:

$$\tau_0 = 10^5 x^{-2.39}$$

where x is temperature in ˚C. The tau-temperature relationship showed an inverse correlation and ranged from 73.5 to 30 minutes in the observed temperature range.

Discussion

Ovulation based on the light cycle was a reasonable means for predicting time of stripping. Hormonal induction of ovulation would seem to be a logical method for determination of egg collection; however, cichlids have responded poorly to gonadotropic therapy (Rana, 1988). On the other hand, the physiological characteristics of tilapia gametes provide an advantage in chromosome manipulation. Eggs retain high fertility for three to six hours post-immersion in water (Myers et al., 1995) and sperm remain motile in water for several hours in contrast with most fishes (Yeheskel and Avtalion, 1986). Thus, the quality of gametes should not deteriorate during UV treatment in comparison with other fishes.

More suitable incubation techniques must be incorporated in the chromosome manipulation protocol, since survival is lower for genome-manipulated progeny (Rana, 1986; Mair, 1993). Down-flow incubators should be evaluated in future work.

A reasonable first estimate of a tau curve was developed for Nile tilapia used in this study but additional data should be incorporated. The working curve can be used to standardize shock treatments. The next aspect of this research will be the development of UV treatment of eggs. Treatment of sperm with UV has been routine for the induction of gynogenesis but few studies have attempted androgenesis, which requires egg treatment. Even fewer studies have used UV in female genome deactivation. Preliminary trials have verified the general dosage level (400 to 600 J m^{-2}) reported by Myers et al. (1995). Additional trials will be conducted before attempting diploidization experiments. Finally, shock treatment protocol will be the next research priority. While some guidance is available in the literature for late shock to induce tetraploidy and mitotic gynogenesis (Hussain et al., 1993; Don and Avtalion, 1988a; Mair; 1993), only one study has developed androgenetic protocol for tilapia (Myers et al., 1995).

Thermal shock treatments will be used for practical reasons and because their effectiveness is comparable to or better than pressure shock. Don and Avtalion (1988a) used a cold shock treatment for tetraploidy induction based on its comparative effectiveness for triploidy induction (Don and Avtalion, 1988b). However, the timing for shock reported by Myers et al. (1995) at 27 minutes post-activation (28˚C) contradicts the optimal shock time of 92 minutes post-activation (26˚C) reported by Don (1989) and Shirak (1986), even when adjusted for temperature. Therefore, these reported optimal times and shock types will be examined within the context of tau information.

A visual genetic marker is vital in chromosome manipulation studies. One option with Nile tilapia is the use of normal-color females and males of the blond mutant (McAndrew et al., 1988). This homozygous recessive trait would usually be appropriate; however, the Ivory Coast stock of Nile tilapia at the University of Oklahoma has been subject to some introgression of the blond gene. Alternatively, the red mutant, which is a dominant gene (McAndrew et al., 1988), could be used for an egg source and normal-color males as sperm donors. I will obtain verified homozygous red mutant stocks from Israel. While developing the red mutant line, androgenetic experimentation shall proceed using the current Nile stock and a gold mutant of *O. mossambicus* (Tave et al., 1989) as the sperm donor.

Anticipated Benefits

The development of androgenesis for *O. niloticus* should provide an alternative method for producing YY-males for the monosex production of tilapia.

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Steroid Immersion for Masculinization of Tilapia

Eighth Work Plan, Reproduction Control Research 2 (RCR2) and 3 (RCR3)

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Introduction

The production of single sex populations offers several advantages in tilapia aquaculture, including enhanced growth and prevention of unwanted reproduction. A number of androgens have been shown to masculinize various tilapia species, including 17α-methyltestosterone (MT; summarized by Pandian and Varadaraj, 1990 for *Oreochromis mossambicus*); mibolerone (Torrans et al., 1988 with *O. aureus*); fluoxymesterone (Phelps et al., 1992 with *O. niloticus*); norethisterone acetate (Varadaraj, 1990 with *O. mossambicus*); 17α-ethynyltestosterone (Shelton et al., 1981 with *O. aureus*); 17α-methylandrostendiol (Varadaraj and Pandian, 1987 with *O. mossambicus*), and trenbolone acetate (TBA) (Galvez et al., 1996 with *O. niloticus*).

Aquaculturists usually administer hormones to fish through the diet, but this method is prone to inefficiencies such as uneven exposure to steroid due to the establishment of feeding hierarchies or the availability of supplemental feed from pond primary productivity. Immersion of tilapia fry in steroid solutions may be one way to achieve masculinization and avoid these inefficiencies.

This technique is well-developed in salmonid aquaculture (Piferrer and Donaldson, 1989; Feist et al., 1995); however, it remains largely experimental in tilapia culture. Most of the reported studies immersed tilapia fry in androgens for periods of one to five weeks (Varadaraj and Pandian, 1987; Torrans et al., 1988). Recently, Gale et al. (1995) demonstrated that immersion for just three hours in 17α-methyldihydrotestosterone (MDHT) on two days resulted in masculinization of Nile tilapia. The study described below was undertaken to determine if these findings could be extended through examination of the effects of:

1. rearing density on efficacy of MDHT immersion,
2. a single immersion in MDHT, and
3. immersion in TBA.

Methods and Materials

Breeding families of Nile tilapia *(Oreochromis niloticus)* obtained from Auburn University were placed in 200-l aquaria (one male to three females). The temperature was maintained at 28 ± 2°C. Time of spawning was monitored every 2 hours. All spawning occurred between 1600 h and 1900 h. Once breeding occurred, the other fish were removed leaving the brooding female to incubate the progeny. At 280 Celsius Temperature Units (CTU) post-fertilization, fry were removed from the tank and randomly assigned to experimental groups (CTU are calculated by multiplying mean temperature by the number of days, e.g., ten days at 28°C = 280 CTU). Two hundred and eighty CTU was used as a reference because Gale et al. (1995) obtained 90 to 100% masculinization by immersing fry on day 10 and day 13 post-fertilization (dpf) while maintaining the brooding females at a mean temperature of 28°C. Each treatment within an experiment was replicated two or three times depending on the number of fry available and the objective of the experiment. The fry used in each experiment came from a single female. Each replicate was housed in a 3.8-l glass jar containing dechlorinated tap water maintained at 28 ± 2°C under constant aeration. Treatments consisted of immersions in either steroid or ethanol, which were mixed one minute before addition of fry. Steroids were obtained from Sigma Chemical Company (St. Louis, Missouri) and stored in stock solutions of ethanol (1 mg ml^{-1}). The following provides a description of each treatment:

Experiment 1: Effects of Density

Fry were immersed for two hours in 500 µg l^{-1} of MDHT at 280 and 364 CTU (10 and 13 dpf at 28°C) using 33, 67, 100, or 200 fish l^{-1} in each replicate. Fish in the control group were immersed in 0.5 ml^{-1} of ethanol vehicle (ETOH) using 33 fish l^{-1} in each replicate. Each experimental group was conducted in triplicate with the exception of the 200 fish l^{-1} density in which the number of fry in the brood permitted only one replication for this treatment.

Experiment 2: Effect of Number and Timing of Immersions

Fry were immersed either once for two hours at either 280, 310, or 364 CTU (10, 11, or 13 dpf), or twice at either 280 or 364 CTU in 500 µg l^{-1} of MDHT at a density of 33 fish l^{-1} in each replicate. Fish in the ETOH control group were immersed at 280 and 364 CTUs. Each experimental group consisted of two replicates, whereas feed treatments consisted of three replicates.

Experiment 3: Effects of Steroid and Mode of Application

Fry were fed 60 mg of MT kg^{-1} of food for 28 days at a density of 47 fish per jar (field densities were proposed by Popma and Green, 1990). Immersion treatments consisted of 33 fish l^{-1} immersed at 292 CTU for 48 hours in either MT or TBA; at 310 CTU for two or four hours in TBA; and two immersions at 310 and 364 CTU each for two hours in either MT or TBA. All steroid immersion concentrations were 500 µg l^{-1}. Two control groups were incorporated—one used food treated with ETOH and the other involved fry immersion for four hours in water containing 0.5 ml of ETOH vehicle at 310 CTU. For each experiment, fry were collected after each immersion, jars were thoroughly cleaned, and then fish were reallocated in fresh, dechlorinated tap water. After seven days, fry were transferred to Oregon State University's Warm Water Research Laboratory, Corvallis, Oregon, and reared in 75-l fiberglass tanks with a recirculating system. Temperature and pH were monitored daily; ammonia, nitrites, dissolved oxygen, alkalinity, and hardness were checked weekly. Water temperature in the grow-out system was maintained at 28 ± 2°C. At 60 to 70 dpf fish were weighed and sex ratios were determined. Gonads were stained with aceto-iron hematoxlin (Wittman, 1962) and examined, to determine sex, using squash (10 and 40 x magnification) preparations.

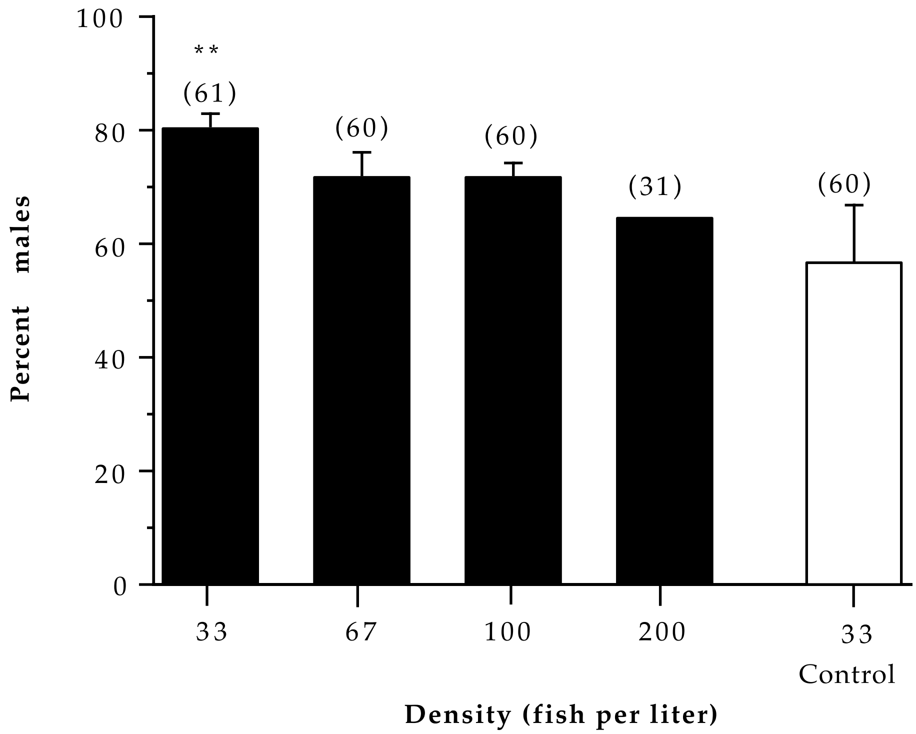

Figure 1. Masculinizing effects of double MDHT immersions on *Oreochromis niloticus* fry at different densities. Sample size is shown in parentheses. ** Indicates significant difference to control ($P < 0.01$). Error bars = SE.

Data were pooled from replicate tanks because there was no evidence of tank effects within treatments (Fisher's test or ANOVA). Sex ratio and mortality data were analyzed using Fisher's exact test with exact p-values (a more conservative test than the chi-square test for small sample sizes) estimated in GraphPad Prism™. The mean final weights of sampled fish from experiments two and three were analyzed for differences between groups using one-way ANOVA; mortality was included as a possible confounding variable. For all analyses differences were considered statistically significant when the p-value (P) was less than 0.05.

Results

Experiment 1: Effects of Density

Treatment with MDHT resulted in masculinization of tilapia (Figure 1). The percentage of males in the 33 fish l^{-1} treatment (80.3%) was significantly higher than the percentage of males in the control group (56.7%); ($P = 0.004$); whereas the percentages of males in the 67 and 100 fish l^{-1} treatments (both treatments produced 71.7% males) were not significantly different from controls ($P = 0.06$). The proportion of males in the only replicate of the treatment with 200 fish l^{-1} (64.5%) was not significantly different from the control group.

Experiment 2: Effect of Number and Timing of Immersions

Single immersion in MDHT at 364 CTU resulted in 79.3% males (Figure 2), which was not significantly different from the two immersions at 280 and 364 CTU (82.9% males). Each of these treatments had a significantly higher proportion of males than the ETOH control group (56.6% males; $P < 0.001$). No significant masculinization effects were observed in groups immersed in MDHT at either 280 or 310 CTU.

Experiment 3: MT Fed, TBA, and MT Immersions

The control fry used for the MT fed and TBA immersion treatments in this experiment showed female-biased sex ratios (15.6 and 13.2% males, respectively) (Figure 3). No significant differences were found between control groups and MT-fed fish (14.1% males); or between control and tilapia

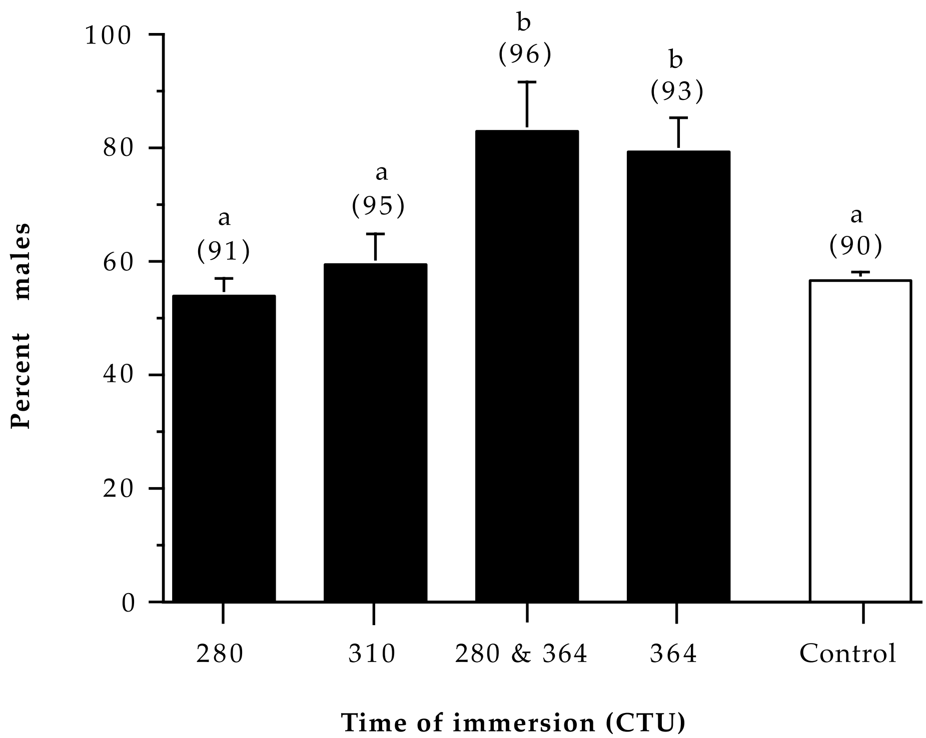

Figure 2. Masculinizing effects of single and double MDHT immersions on *Oreochromis niloticus* fry. Sample sizes are shown in parentheses. Treatments annotated with the same letter (a or b) are not significantly different. Error bars = SE.

immersed in TBA for two hours at 310 CTU (20.0% males), or between control and tilapia immersed in MT for two hours at 310 ad 364 CTU (20.0% males). Single immersions in MT (26.7% males produced) and TBA (37.3% males produced) for 48 hours at 292 CTU resulted in higher proportions of males ($P = 0.049$ and 0.002, respectively). Immersions in TBA for four hours at 310 CTU and two hours at 310 and 364 CTU produced significantly higher proportions of males (64.4 and 91.9%, respectively) ($P < 0.001$).

In all experiments mortality and final weight data were not significantly different among treatment groups. Water quality in rearing tanks was maintained close to the optimal values for tilapia culture (data not shown).

Discussion

We have demonstrated that short-term steroid immersion can result in masculinization of Nile tilapia as reported by Gale et al. (1995). A single immersion in MDHT at 364 CTU (13 dpf at 28°C) was as effective as two immersions at 280 and 364 CTU. Our experiments did not result in the level of masculinization (> 93%) that Gale et al. (1995) achieved; however, the Gale et al. (1995) study used two 3-hour immersions, whereas we used two 2-hour immersions in this study. The increased effectiveness of longer duration single exposures was further demonstrated in the experiment utilizing TBA. A two hour immersion in TBA did not cause significant masculinization in the female-biased brood, but a four hour immersion did result in more males than in the controls.

The ratios of males produced by MDHT immersion at the 67 and 100 fish l^{-1} stocking densities were nearly significantly different to controls, which suggests that stocking density may affect masculinization. At a stocking density of 33 fish l^{-1}, nearly five times the stocking density reported by Torrans et al. (1988) in a study in which *O. aureus* were masculinized by immersion for five weeks in mibolerone, MDHT caused significant masculinization with either one or two immersions. The lack of significant masculinization of tilapia exposed to MDHT for two hours at 280 or 310 CTU suggests that the period of sensitivity to steroid-induced masculinization is several days after the

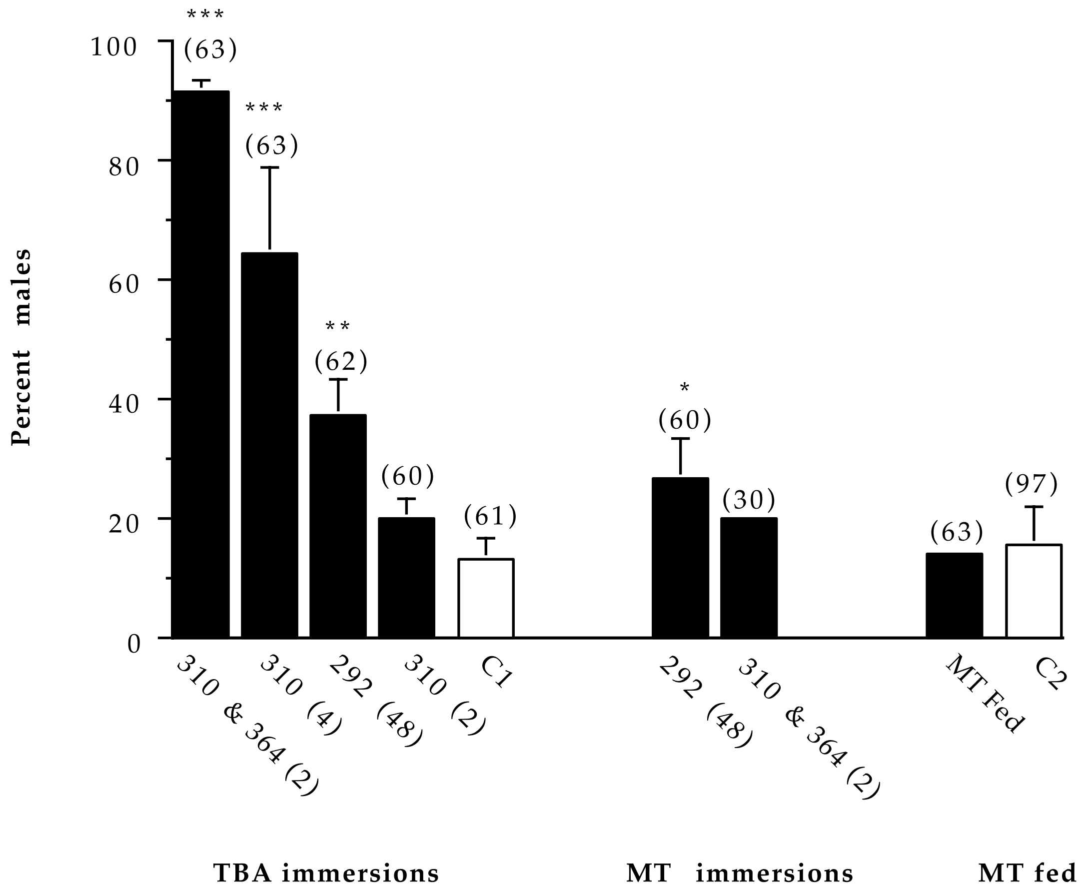

Figure 3. Masculinizing effects of TBA, by immersion, and of MT, by immersions and feeding, on *Oreochromis niloticus* fry. Treatment names are given as CTU at immersion with duration of immersion (h) in parentheses. Sample sizes are shown in parentheses at the top of each bar. Statistically significant differences are represented by asterisks (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$). Immersion treatments were compared with ETOH immersion control (C1) and the MT-fed treatment was compared with the ETOH-fed control (C2). Error bars = SE.

onset of feeding. However, immersion for 48-hours in TBA or MT, commencing at 292 CTU skewed the sex ratios toward males in the female-biased brood. In contrast with tilapia, salmonids must be immersed as yolk-sac fry (Piferrer and Donaldson 1989; Feist et al. 1995).

Two 2-hour immersions in TBA produced over 90% males in the female-biased brood in comparison with 20% males produced in two 2-hour immersions in MT. Interestingly, this brood of fish did not demonstrate any masculinization despite four weeks of feeding with MT diet. This result is rarely reported in the literature, but based on anecdotal information. This may be a common phenomenon, thereby pointing to the need for further research of immersion treatment as an alternative to dietary treatment for masculinization.

Anticipated Benefits

The use of all-male populations of tilapia for culture offers several important advantages, including enhanced growth (males grow faster and larger) and prevention of unwanted reproduction (which diverts energy away from somatic growth). Treatment with methyltestosterone-impregnated food has been shown to be an effective means of producing all-male tilapia populations. However significant "leakage" of steroids such as MT into the pond environment may occur from uneaten or unmetabolized food and thus pose a risk of unintended exposure of hatchery workers or non-target organisms. Development of immersion in steroid as an alternative treatment for masculinizing tilapia will minimize treatment time and potentially increase the efficiency of exposure and safety in handling masculinizing steroids.

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Economic and Social Returns to Technology and Investment

Eighth Work Plan, Marketing and Economic Analysis Research 1 (MEAR1)

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Introduction

The Pond Dynamics/Aquaculture CRSP is a global research activity directed toward improving the sustainability and efficiency of pond aquaculture production. The benefits of this effort will be the economic and social returns to farmers who have adopted new technologies developed by the PD/A CRSP.

Technical progress has been modeled as a lagged function of research expenditures by Chavas and Cox (1992). This study identified and measured the length of time required to fully translate public research expenditures into economic benefits and estimated internal rates of return for research expenditures. In the Chavas and Cox model, there were no restrictions on substitution possibilities among inputs, joint estimation of the production technology, technical change, and the effects of research on technical progress using disaggregate inputs. This approach required only a standard linear programming algorithm. Ardito-Barletta (1971), Ayer and Schur (1972), and others estimated social rates of return to the investment in public research.

White (1985), in a study valuing research as an intangible capital in agriculture using Tobin's *q* theory, estimated the market value of public research capital to be 8.6 times higher than conventional assets. Private research capital was valued 5.2 times higher than conventional assets.

Fischer et al. (1996) used a random-effects model within a Bayesian framework to analyze the effect of the adoption of new wheat varieties in South Australia. Results showed that not all pieces of information added equally to knowledge about the innovation. The random effects model also provided a more accurate simulation of the speed of acquisition of information, which previous models over-estimated, and was able to take into account partial adoption of innovation.

Huang and Sexton (1996) developed a general, imperfect competition model to evaluate returns to a cost-reducing innovation. In an imperfectly competitive market structure, this study showed that farmers' incentives to adopt a mechanical harvester for tomatoes in Taiwan were attenuated because the benefits were reduced due to the oligopsonistic power of processors.

Dorfman (1996) used a multinomial probit model to simulate adoption decisions faced by farmers when there are multiple technologies available to be used in varying combinations. Results showed that the decision to adopt potentially sustainable production technology bundles was significantly influenced by off-farm labor supply.

Fuglie (1995) developed a multimarket model to explore equity and efficiency implications of improving crop storage technologies. The rate of return on research on potato storage in Tunisia was estimated to be between 44 and 74%.

Methods and Materials

Theoretical Model

The section entitled "Model Development and Data Requirements" mentions the theoretical considerations and describes the model developed for the analysis of data from this study. Supply and demand equations will be estimated to identify the areas in the graphs labeled as "Consumer Surplus" and "Producer Surplus". Research that leads to the development and adoption of new technologies reduces the cost of production which further causes a reduction in the cost to the producers. The combined changes in the net gain to producers and the net gain to consumers are the social gain from research. Therefore, this study hypothesizes that new technologies produced from CRSP-funded research result in a net increase in economic surplus.

Data

The "Model Development and Data Requirements" section also lists the parameters to be estimated to conduct impact analysis for both shrimp and tilapia growers in Honduras. Specific CRSP technologies that will be evaluated include feeding recommendations for shrimp growers and sex-reversal technologies for tilapia growers. Data will be collected through surveys of shrimp and tilapia growers. Survey instruments have been designed and are currently under review. After review the instrument will be translated into Spanish, pre-tested, and then administered. The Asociacion Nacional de Acuicultores de Honduras (ANDAH) and the Federacion de Agroexportadores de Honduras (FPX) have been contacted for support in administering the survey. A follow-up trip to finalize data collection is planned for September 1997.

Data will be coded and entered into a LOTUS 1-2-3 spreadsheet for summarization and cross-tabulation. The model presented above will perform simulations for each set of survey data and estimate the net social gain from CRSP-developed technology.

Model Development and Data Requirements

Economic and production relationships are used as the basis for modeling technical progress in fish farming technologies. Following Chavas and Cox (1992), technical progress is modeled as a lagged function of research expenditures. The advantages of such an approach are:

1. substitution possibilities among inputs are not restricted;
2. it allows for the use of very disaggregate inputs, joint estimation of the production technology, technical change, and the effects of research on technical progress;
3. the investigation of the length and shape of the lag distribution between research and productivity is flexible; and
4. only a standard linear programming algorithm is required.

The length of time required to fully translate public research expenditures into economic benefits will be estimated along with internal rates of return for the research expenditures. Following Ayer and Schur (1972) and Ardito-Barletta (1971), social rates of return will be estimated and both supply-shifting (cost-reducing) and demand-lifting (quality improvement) effects of new technologies will be assessed.

Given the collaborative nature of the PD/A CRSP projects, it is necessary to evaluate the net social welfare resulting from the implementation of these projects. Welfare economics are concerned with policy recommendations; however, they can also be used as an evaluation tool to determine the social impact of a given project. In a attempt to measure PD/A CRSP impact, a function describing the net social benefits can be estimated. The different groups involved in these projects are usually not mutually exclusive, and in conjunction with the compensation criterion, social welfare can be measured as follows:

$$w = \Pi_Q = CS_Q + PS_X + E - G$$

where

w = net social benefits (positive or negative),

Π_Q = the profit or rent accruing to PD/A CRSP researchers,

CS_Q = consumers' surplus in the host country which can be measured as surplus for final consumers plus all forward rents,

PS_X = producers' surplus measured as rent inputs plus all backward rents plus surplus for raw materials,

E = external benefits/costs,

G = the social overhead cost for PD/A CRSP programs.

As suggested by Alston et al. (1995), methods of production economics can be used to evaluate the effects of aquacultural research. However, the evaluation should progress beyond a simple estimation of the input-output relationship. Consequently, the framework suggested by Masters et al. (1996) was adopted to evaluate past research investment (see Appendix).

Anticipated Benefits

Results of this study will provide justification for the continued funding of PD/A CRSP research through quantification of the program's benefits and impacts. This study will provide the first estimates of the social and economic returns generated by the PD/A CRSP over time.

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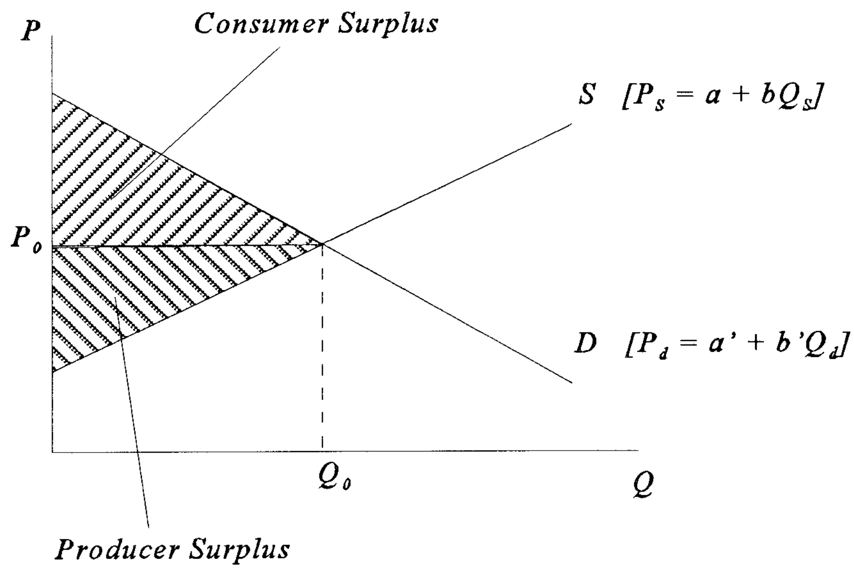
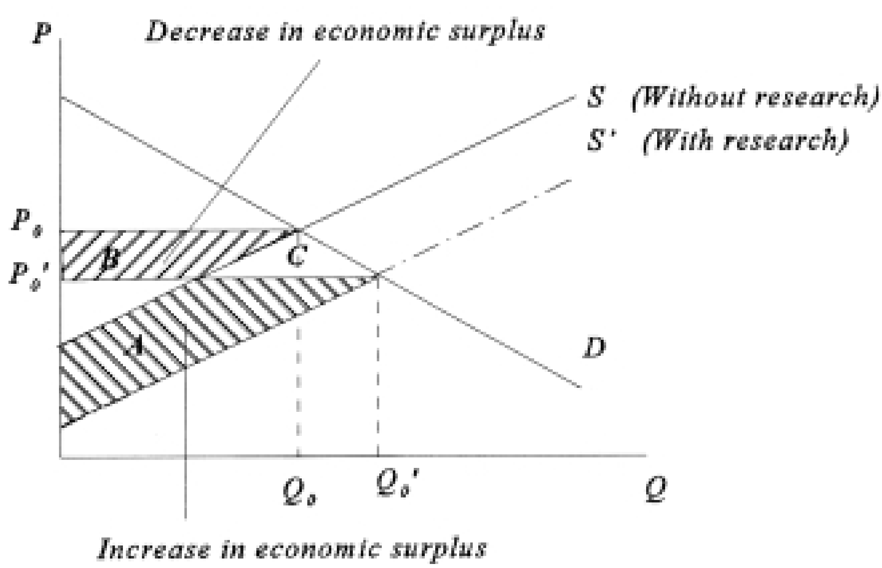
APPENDIX: A FRAMEWORK TO EVALUATE PAST RESEARCH EFFORT

Consumer and Producer Surpluses (Economic Surplus)



Research Impact



Research reduces cost of production and price to producers.

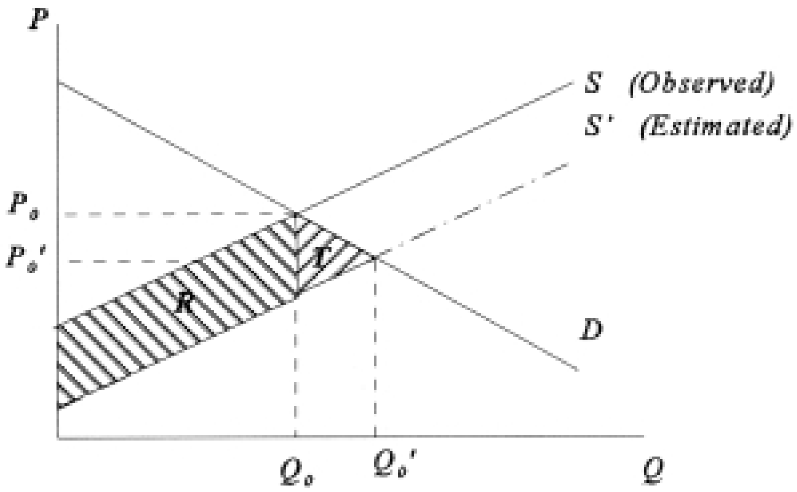
Producers net gain (PNG) = (A - B).

Consumer net gain (CNG) = (B + C).

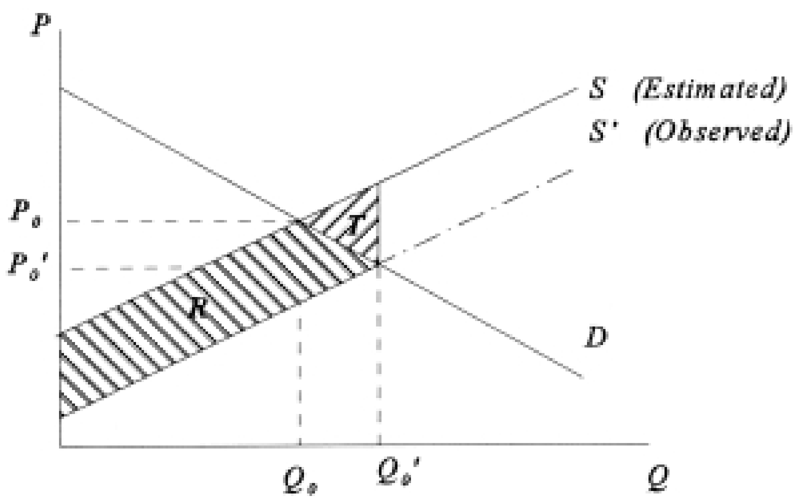
(A + C) can be viewed as social gain for research.

APPENDIX: continued

Ex-Ante Evaluation of the Impact



Ex-Post Evaluation of the Impact



Let $\Delta Q = Q_0 - Q_0$ denote the change in total quantity observed due to research, and let k denote the vertical movement factor of the supply curve.

Social gain (SG) can be expressed as:

$$SG = kQ_0 \pm \frac{1}{2} k\Delta Q$$

where

(+) is used for ex-ante and (–) for ex-post evaluations,

Q is known,

k and ΔQ are unknown and need to be estimated.

APPENDIX: continued

The following are the necessary parameters to be estimated and data requirements:

- Increase in productivity (ΔR) (kg ha^{-1})
- Adoption cost (ΔC) in terms of land area moved from one activity to new activity
- Adoption rate (t) in terms of % increase in acreage devoted to activity (or in terms of new entrants)
- Total area in production (S) (ha)
- Total production (Q) (kg or tons)
- Average production/productivity (R = Q/S) (kg or tons)

To be estimated:

1. Let $J = \Delta R * t * S$

   J can be viewed as total increase in production due to technology adoption, holding cost, and prices that remain constant.

   Let j be the change in supply or coefficient by which the supply curve has moved with the new technology, $j = (\Delta R * t) / R = J / Q$

2. $I = \Delta C * t / R$

   I is the increase in cost of inputs per unit necessary to achieve J. I can be calculated proportionally to observed price (P) such that $c = I / P = (\Delta C * t) / (R * P)$

3. Let $K = (b * J) - I$

   b is the supply curve slope; K represents the net reduction in production cost due to technology (vertical movement of the supply curve). In fact, the coefficient b is not used, the supply elasticity $(\in_S)$ is used instead.

   $$\in_S = (\Delta Q / \Delta P) * (P / Q) = (1 / b)(P / Q)$$

   this leads to:

   $$\in_S * b = P / Q$$
   $$b = (1/ \in_S) * (P / Q)$$

   therefore,

   $$K = [(1/ \in_S) * (P / Q) * J] - I = (P * J / \in_S * Q) - I$$

   With respect to price (P),

   $$k = K / P = [(P * J / \in_S * Q) - I] / P = (P * J / \in_S * Q * P) - (I / P) = [(1/ \in_S) * (P * J / Q * P)] - (I / P)$$
   $$k = (1/ \in_S) * j - c$$

   When supply is inelastic $(\in_S < 1)$, an increase in production due to research has a relatively high economic value $(k > j - c)$ possibly limited acreage. Elastic supply $(\in_S > 1)$, possibly abundant acreage, $\in_S$ reduces $k (k < j - c)$. In this latter case, it is easy to increase production and research gains have little economic value.

APPENDIX: continued

4. ΔQ depends on supply movement and response of supply to demand.

At equilibrium:

$$Q_s = Q_d$$
$$a + bP = a' + b'P$$
$$P = (a - a')/(b' - b)$$

with research, equilibrium corresponds to new supply curve which moved with price increase:

$$Q_s' = Q_d$$
$$a' + b'P' = a + bK + bP'$$
$$P' = (a - a' + bK)/(b' - b)$$

In terms of change in price (ΔP):

$$\Delta P = P' - P$$
$$\Delta P = -bK/(b' - b) = bK/(b' - b)$$
$$\Delta Q = b'\Delta P = b'bK/(b' - b)$$

Elasticity of demand $(\in_d)$

$$\in_d = (\Delta Q/\Delta P)(P/Q) = b'(P/Q)$$
$$b' = \in_d/(P/Q) = \in_d(Q/P)$$

In terms of change in production (ΔQ):

$$\Delta Q = [(\in_d(Q/P))(\in_s(Q/P))K]/[(\in_d(Q/P)) + (\in_s(Q/P))]$$
$$\Delta Q = \in_d \in_s (Q^2/P^2)/[(\in_d + \in_s)(Q/P))]$$
$$\Delta Q = Q \in_d \in_s k/(\in_d + \in_s)$$

Risk Analysis of Pond Management Strategies

Eighth Work Plan, Marketing and Economic Analysis Research 2 (MEAR2)

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Introduction

Technology adoption occurs at the micro, or farm level. A farmer's decision to adopt a new technology will depend upon many factors that range from simple costs and returns to market factors to complex interactions between the new technology and the farming system practiced by the farmer. The specific objective of this study was to analyze the integration of pond fertilization schemes into farming systems including explicit treatment of risk factors. Environmental factors will be included in a model to fully assess sustainability from ecological, economic, risk, and food security viewpoints.

The nature of fish and livestock production, in conjunction with the adoption of new technologies, changing market structure, and environmental conditions, affects prices and can lead to variations in farmers' income and decision-making. A farmer's expectation of a higher return as compensation for an increase in risk denotes a "risk aversion" behavior. A risk averter can, therefore, diversify his portfolio over different assets. "Unless these risk responses are adequately reflected in planning models, the results generated in empirical analysis may bear little resemblance to actual decisions and may be of little use either in direct decision-making or in policy analysis" (Boisvert and McCarl, 1990).

Risk analysis has been used to analyze several management issues in catfish production. Risk programming mathematical models were developed to compare aeration strategies on catfish farms (Engle and Hatch, 1988). Engle and Pounds (1994) later incorporated risk factors into a two-year model with single- and multiple-batch production systems. This analysis indicated that farmers use multiple-batch strategies, even though profits are lower, rather than single-batch strategies due to off-flavor and cash flow reasons. Engle et al. (1995) extended this analysis to estimate off-flavor costs on catfish farms by including farm-level off-flavor data sets. Hatch and Atwood (1988) used risk programming to analyze catfish production.

Methods and Materials

Theoretical Model

Cost and return data from Thailand for fish and livestock production, along with fish growth models (Springborn et al., 1992) will be used to construct a mathematical model of aquaculture production.

In this type of analysis, a "typical farm" is modeled in terms of key economic parameters. These include: extent of land holdings, quantity of labor available (both family and hired), investment capital, and operating capital available. These are determined from published surveys, from statistical service reports, and in consultation with host country personnel. The set of alternative agricultural crops is again specified in conjunction with host country personnel and extension workers. Annual cost and return estimates from published enterprise budgets are used to develop technical coefficients for the model. In the case of Thailand, these are developed for several types of aquaculture and livestock alternatives. If available, cost and return estimates will be used for horticulture crops; however, if they are not available the analysis will focus on livestock alternatives.

Risk functions will be incorporated to assess the following potential benefits of aquaculture; the direct financial and nutritional benefits of fish production in the event that staple crops produce low yields, and the indirect benefit of a source of irrigation water provided by fish ponds.

Given the risk aversion behavior of farmers and the assumption that decision-makers are concerned about income falling below some minimum level, a "safety-first" model will be developed to conduct the analysis. The model can be viewed as a mean-risk dominance model in which risk will be measured by a probability-weighted function of deviations below a specific target return. In practice, a Target MOTAD or a Mean-Gini model can be developed as a second degree stochastic dominance model which assumes a restriction of risk aversion and includes functions that represent risk averse individuals.

The following is the general formulation for a Target MOTAD model:

Maximize $$\sum_{j=1}^{n} T_j X_j$$

Subject to

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i \qquad \text{for all } i;$$

$$\sum_{j=1}^{n} c_{kj} X_j + Y_k \geq T \qquad \text{for all } k;$$

$$\sum_{k=1}^{k} P_k Y_k \leq \lambda$$

$$X_j Y_k \geq 0 \qquad \text{for all } j \text{ and } k$$

Where

- Xj refers to decision variables;
- cj refers to uncertain parameters that have means Tj;
- P_k is the probability of the kth state of nature;
- T is the target income level;
- Y_k is a negative deviation of income under the kth state of nature below the target income;
- λ is the maximum amount subject to the normal resource constraints and two new constraints.

The key assumptions of the model are that economic returns are normally distributed and that the expected value of technical coefficients is the mean. Risks are not assumed by the model, but will be determined in consultation with host country and extension personnel. Typically, risk is associated with production, market, or financial factors. Economists define risk as the variability in crop yields, prices, and interest rates. Price and interest rate data will be obtained from secondary sources, whereas the variability in crop yields will be estimated by developing a probability distribution based on CRSP-generated data.

Data

Data will be collected through surveys of shrimp and tilapia growers from Honduras. Survey instruments have been designed and are currently under review. The instruments will, after review, be translated into Spanish, pre-tested, and then administered. The Asociacíon Nacional de Acuicultores de Honduras (ANDAH) and the Federacion de Agroexportadores de Honduras (FPX) have been contacted for support in administering the survey. A follow-up trip to finalize data collection is planned for September 1997.

Data will be coded and entered into a LOTUS 1-2-3 spreadsheet for summarizing and cross-tabulation. The model presented above will be estimated for each set of survey data and the net social gain from CRSP-developed technology will be estimated.

Anticipated Benefits

This study will provide important insights on the integration of CRSP technologies into host country farming systems and is intended to provide recommendations for increasing incomes of farmers and rural communities. These results will primarily benefit CRSP researchers and beneficiaries in Honduras. Future studies will be conducted at other CRSP prime sites. As research is conducted at additional sites, results across studies should reveal more global indications regarding the usefulness and effectiveness of CRSP-generated technologies.

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Advances in the POND© Software: Wizard Development and Model Refinements

Eighth Work Plan,
Decision Support Systems Research 1A, 1B, and 1D (DSSR1A, 1B, and 1D)

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Introduction

The POND© software developed by researchers at Oregon State University is in its third phase of iterative refinement. The first phase of software development was incorporated in POND© Version 2.0. POND© Version 3.0 included second phase refinements—the consideration of water budgets, preliminary assessment of feed quality and of nutrient fluxes in pond sediments, improved routine fertilization guidelines, and parameter estimation techniques. This report documents improvements that have been made to POND© in terms of model refinements and enhanced capabilities for decision support.

POND© Wizards

Our interaction with POND© users over the past few years has indicated that occasionally a lack of understanding exists concerning the types of problems POND© analyzes and the procedures required to accomplish analysis. An effort was therefore initiated to add several "wizards" or "experts" to the software to automate the procedures for undertaking analyses of pond facilities. The wizards currently available include:

- A *pond setup* wizard that enables users to define new ponds at their facility;
- A *lot setup* wizard that enables users to define new lots that are associated with specific ponds;
- A *fertilizer* wizard that generates routine pond fertilization recommendations;
- A *liming* wizard that estimates lime requirements for ponds with specific soil types;
- A *feed optimizer* wizard that generates feed schedules to minimize the amount of feed needed for a specified fish target weight; and

- A *simulation* wizard that conducts facility-level simulations at a given site and presents simulation results in graphical and tabular formats.

Each wizard performs its designated tasks in a consistent manner that involves a series of dialog boxes which query the user for information relevant to the task in question (Table 1). Users are able to proceed once the information requested in a specific dialog box has been provided and have the opportunity to return to a previous dialog box if any settings are to be edited. This flexible design may be beneficial to a range of POND© users, from beginners to experienced personnel. The incorporation of "wizards" in POND© software has been well received by potential users, including selected attendees of the National Aquaculture Extension Conference (8-11 April 1997) held in Annapolis, Maryland.

Model Refinements

As with any long-term systems analysis activity, refinement of POND© software models is an ongoing effort. Model refinements that have either been completed during the past year or that are presently being evaluated include the following:

- Fertilization effects on fish growth;
- High biomass effects on fish growth in fed ponds;
- Feed type (moisture, protein, and energy content) and feeding level effects on fish performance;
- Phosphorus flux in pond water and sediments; and
- Polyculture interactions in ponds.

Fertilization Effects on Fish Growth

In the previous version of POND©, Version 3.0, the models used at the simplest level of analysis (i.e., Level 1) did not directly account for the effects of fertilization rates on fish growth. Users were required to adjust the critical standing crops or critical fish biomass (CFB) upward or downward to reflect higher or lower fertilization rates, respectively. Estimating fish growth in fertilized ponds requires consideration of the amount of natural food produced and the effects of fish biomass on this food resource.

In the present version (4.0) of POND©, we assume that the amount of natural food produced can be evaluated in terms of the predicted gross primary productivity (GPP) relative to the maximum primary productivity value possible for the site (GPP_{max}) (See Nath, 1996 for a description of the model used to estimate GPP.) Values generated from the natural food scaler ($N = GPP/GPP_{max}$) fall within the range of 0 to 1; higher values indicate good productivity and therefore abundant natural food. However, once the fish standing crop exceeds a user-specified maximum critical fish biomass (CFB_{fert}), natural food availability is expected to decrease. The previous version of POND© (Bolte et al., 1995) expressed the effect of fish biomass using the function CFB_{fert}/CFB; however, this value is further scaled by the use of the parameter N. The overall approach generates profiles of fish growth that vary according to site properties (e.g., light availability), pond performance, and fertilizer application rates. Variation in fish growth profiles is due to the effects of these variables on GPP (Figure 1).

High Biomass Effects on Fish Growth in Fed Ponds

In addition to the effects of fertilization of on fish growth at Level 1, the previous version of POND© also did not account for the possible influences of high fish biomass on growth in ponds that receive supplemental feed. The actual mechanisms, deterioration of water quality, and behavioral change, by which these effects occur can not be adequately addressed without adding substantial complexity to the Level 1 models in the software. The alternate approach currently being implemented involves defining a critical fish biomass below which growth is not adversely affected in fed ponds (CFB_{feed}). To account for high fish biomass effects, the daily fish growth rate (g d^{-1}) is calculated using the POND© fish bioenergetics model and is then multiplied with a biomass scaler (B; 0-1) that is calculated as follows:

$$B = \begin{cases} 1.0 & \text{if } FB < CFB_{feed} \\ CFB_{feed}/FB & \text{if } FB \geq CFB_{feed} \end{cases} \qquad (1)$$

The effect of this scaler on fish growth is indicated for a hypothetical pond stocked with African catfish (*Clarias gariepinus*) in Figure 2. The advantages of this scaler are that it:

1. Enables consideration of biomass effects on growth in fed ponds; and

Table 1. A listing of the wizards in POND©—their functions, the types of information requested from users, and the outcome once the wizards have executed their tasks.

Wizard Name	Function	Information Accessible (by Dialog Box Number)					Outcome
		Box 1	*Box 2*	*Box 3*	*Box 4*	*Box 5*	
Pond Setup	Specify ponds	Pond name Site location	Dimensions	Water balance options	—	—	New pond defined
Lot Setup	Specify lots	Lot name	Species type Associated pond Daily mortality	Stocking date Stocking density Stocking weight	Harvest options	Feeding options	New lot defined
Fertilizer	Estimate fertilizer needs	Pond selection	Model parameters and predictions	Selection of fertilizer(s)	—	—	Least-cost fertilizer mix for weekly addition
Liming	Estimate lime requirements	Pond selection	Associated soil type	Selection of liming material	—	—	Amount and cost of lime required
Feed Optimizer	Optimization of feed use	Site and pond selection	Associated lot parameters	Target fish weight Allowable feed levels	—	—	Optimized feed schedules for culture period
Simulation	Perform facility simulation	Site selection	Selection of ponds to simulate	Associated lot parameters	Graphical or tabular output Enterprise budget	—	Production statistics[1], detailed simulation output, and automated economic analysis

[1] Includes final fish weights, net fish yields, feed requirements and food conversion ratio (if artificial feed is used), and fertilizer and water requirements itemized by ponds and lots.

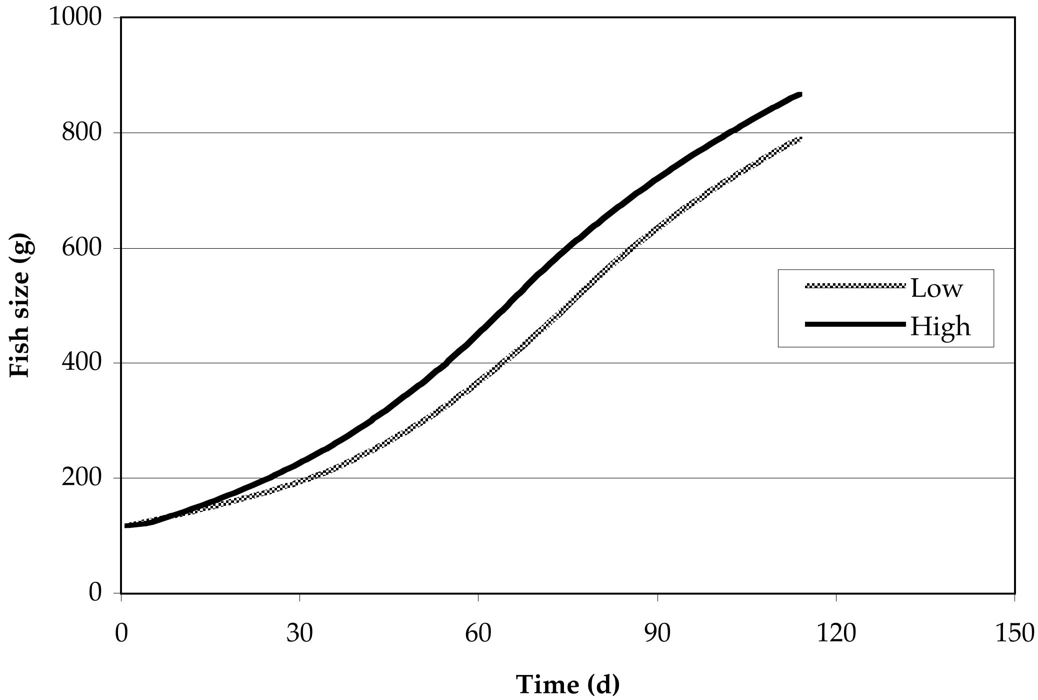

Figure 1. Predicted growth of African catfish in ponds maintained at low (approximately 4 g C m^{-3} d^{-1}) and high (approximately 6 g C m^{-3} d^{-1}) levels of gross primary productivity.

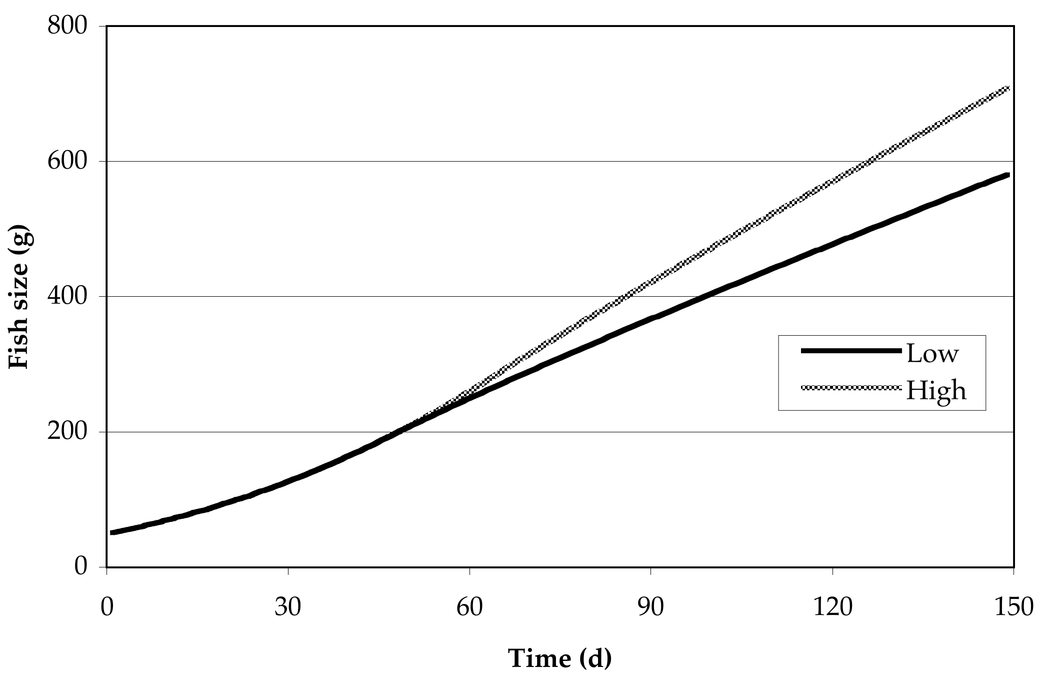

Figure 2. Predicted growth of African catfish in ponds where growth was assumed to be limited at a low (> 3500 kg ha^{-1}) and high (> 5000 kg ha^{-1}) fish biomass.

2. Helps to identify when fish biomass should be thinned to permit the remaining population to continue growing at a rapid rate. Additionally, the scaler may also be useful for determining when improvements to water quality are necessary.

Feed Type and Feeding Level Effects on Fish Performance

A fundamental assumption of the POND© Version 3.0 fish bioenergetics model was that the composition of fish and their diet is identical. This assumption has its roots in Ursin's (1967) growth model which is the basis of our work in the area of fish bioenergetics. However, to adequately account for the effects of supplemental feeds of different quality (primarily in terms of moisture, protein, and energy content) on fish performance, it is necessary to remove the above assumption. Further, the previous version of the bioenergetics model in POND© assumed digestibility to be a constant, even though it depends on the feeding level and other factors. In this section we discuss changes made to the POND© bioenergetics model that account for the effects of the variables discussed above.

Moisture Content

In the present version of POND© (4.0), the ratio of dry matter content of fish (DM_{fish}; g dry matter per g fish) to that of feed (DM_{feed}; g dry matter per g feed) is used to adjust the daily ration (R; g feed per day) for differences in moisture content between fish and the feed material supplied. The expression used is:

$$R = \frac{Wf_s}{q} \times \frac{DM_{fish}}{DM_{feed}} \qquad (2)$$

where

W = fish mass (g),

f_s = fraction of the diet that comprises artificial feed, and

q = feed quality coefficient.

Protein Content

According to Hepher (1988) dietary protein (d_p), expressed as a percentage of dry matter, does not affect fish growth if it is above a critical level (P_{crit}) that is species dependent. As the dietary protein level reduces from P_{crit}, growth tends to decrease at an increasing rate. The following protein scaler (P_s; 0-1) used in the present version of POND© captures this effect:

$$P_s = 1.0 - \exp[p_1 d_p] \qquad (3)$$

where p_1 is a parameter that controls the rate at which P_s changes as d_p decreases.

Energy Content

To account for situations where the dietary gross energy value drops below a critical level (E_{crit}; kcal g^{-1}) that is again species dependent, an approach similar to the one for protein in POND© is used. The corresponding equation is as follows:

$$E_s = 1.0 - \exp[p_2 d_e] \qquad (4)$$

where E_s = energy scaler (0-1), and p_2 is a parameter that controls the rate at which E_s changes as the gross dietary energy value d_e (kcal g^{-1}) decreases.

It is difficult to evaluate growth response to diets that are sub-optimal in both protein and energy content. For simplicity, we assume that when both protein and energy are below the respective critical levels required by the species, the scaler that is most limiting reduces the anabolic term in the bioenergetics model.

Feeding Levels and Digestibility

It is well established that the digestibility (b) of food decreases as the amount consumed by fish increases (Hepher, 1988; Meyer-Burgdorff et al., 1989). In the present POND© bioenergetics model, we assume that digestibility decreases linearly with increased levels of feeding (from maintenance to full satiation). The slope (*e*) of this relationship is estimated as follows (Figure 3):

$$e = \frac{(b_{max} - b_{min})}{(1.0 - f_{maint})} \qquad (5)$$

where

b_{max} = maximum digestibility coefficient (assumed to occur at a maintenance ration),

b_{min} = minimum digestibility coefficient (at satiation); and

f_{maint} = feeding level parameter in the POND© bioenergetics model corresponding to a maintenance ration.

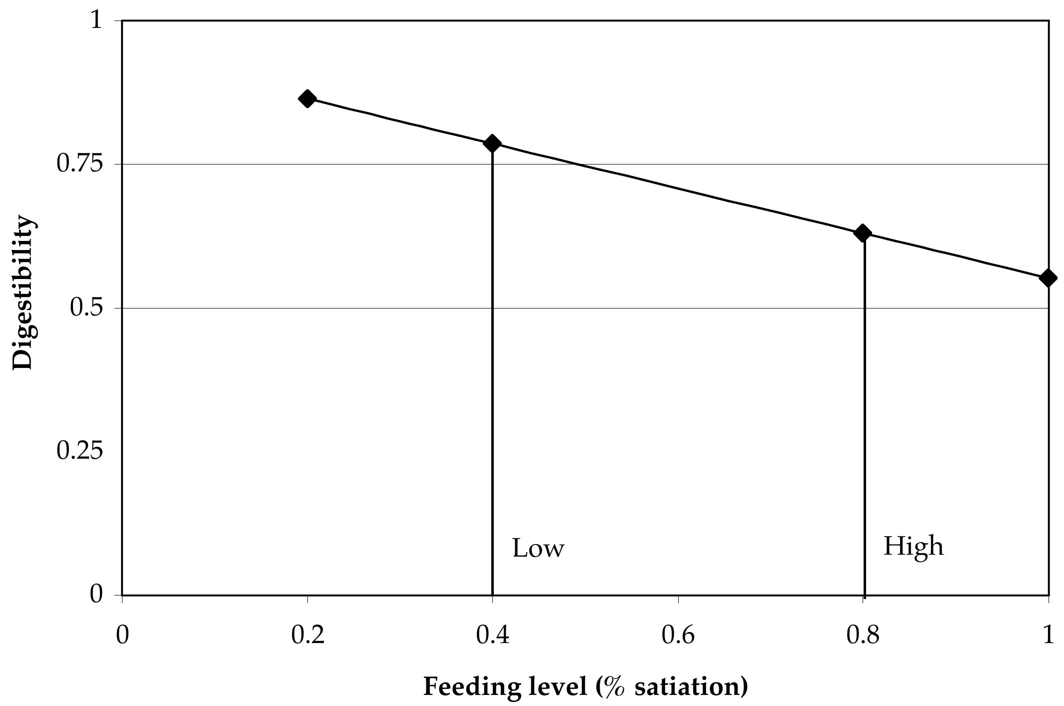

Figure 3. Relationship between digestibility and ration size ranging from a hypothetical maintenance ration to a maximum amount at full satiation. Digestibility values for a low (40% satiation) and a high (80% satiation) ration are also indicated.

Once the slope (e) from Equation 5 is estimated, the actual digestibility coefficient is obtained as follows:

$$b = b_{max} - e(f - f_{maint}) \qquad (6)$$

where

f = feeding level parameter (0-1) for the actual feeding rate.

To use Equations 2 through 6, it is necessary to estimate six new parameters (P_{crit}, E_{crit}, p_1, p_2, b_{max} and b_{min}) , in addition to the previous ones used in the fish bioenergetics model (Bolte and Nath, 1996). Among the six parameters, P_{crit} and E_{crit} can be obtained from bioenergetic studies of different species (reviewed by Hepher, 1988). Four other new parameters have been added to the automatic model calibrator in POND© (Bolte and Nath, 1996), which estimates appropriate values using an adaptive, non-linear search algorithm in conjunction with actual experimental data from pond trials.

At present, the new version of the fish bioenergetics model is calibrated for common carp (*Cyprinus carpio*) and African catfish (*Clarias gariepinus*). A similar calibration for Nile tilapia (*Oreochromis niloticus*), based on growth trials at all the CRSP locations, is presently in progress. Effects of moisture content on carp feeding rates (%BWD) are indicated in Figure 4 for fish that are assumed to have been fed to satiation. The effects of dietary protein and energy content on carp growth are shown in Figures 5 and 6, respectively. Finally, the effects of different feeding levels on the food conversion ratio (FCR) for common carp are shown in Figure 7. The relationship between FCR and ration in the latter figure is consistent with studies that have experimentally demonstrated this profile (e.g., Brett, 1979; Balarin and Hatton, 1979).

In a broader context, the refinements to the POND© bioenergetics model will enable users to perform simulations with different types of feeds and feeding levels and evaluate the implications of simulation results on pond performance, fish growth, and production economics.

Models for Phosphorus Flux in Pond Water and Sediments

A major drawback of current pond aquaculture models is that they do not address the sediment-water interface (Colman and Jacobson, 1991) and

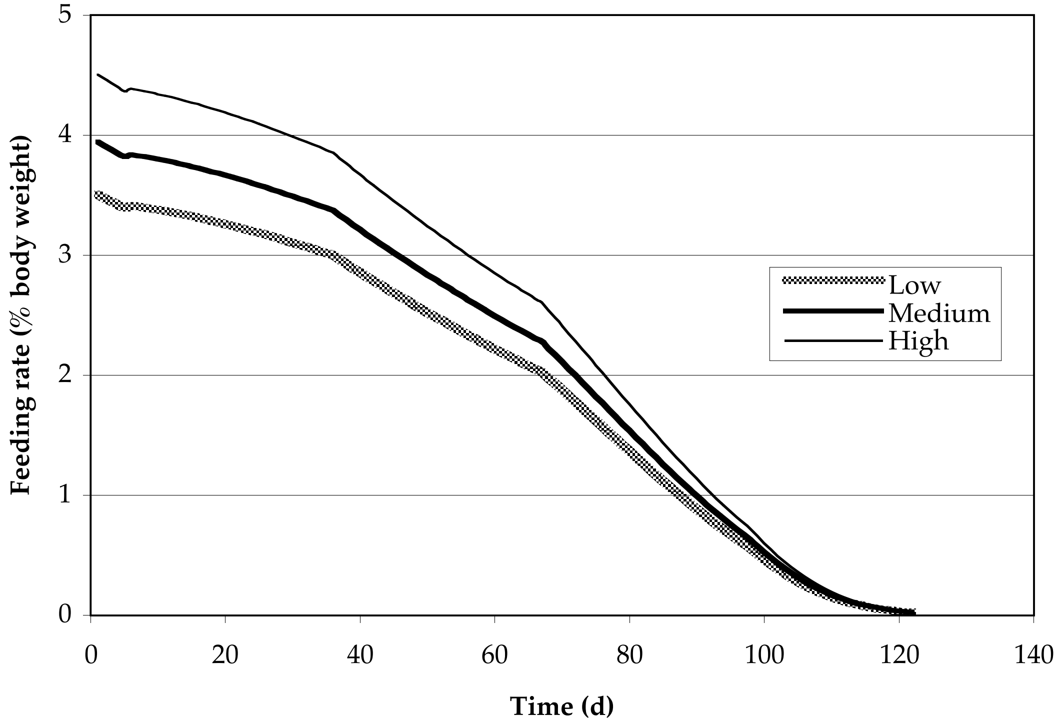

Figure 4. Fish feeding rates predicted by the POND© energetics model for common carp that received low (10%), medium (20%), and high (30%) moisture diets.

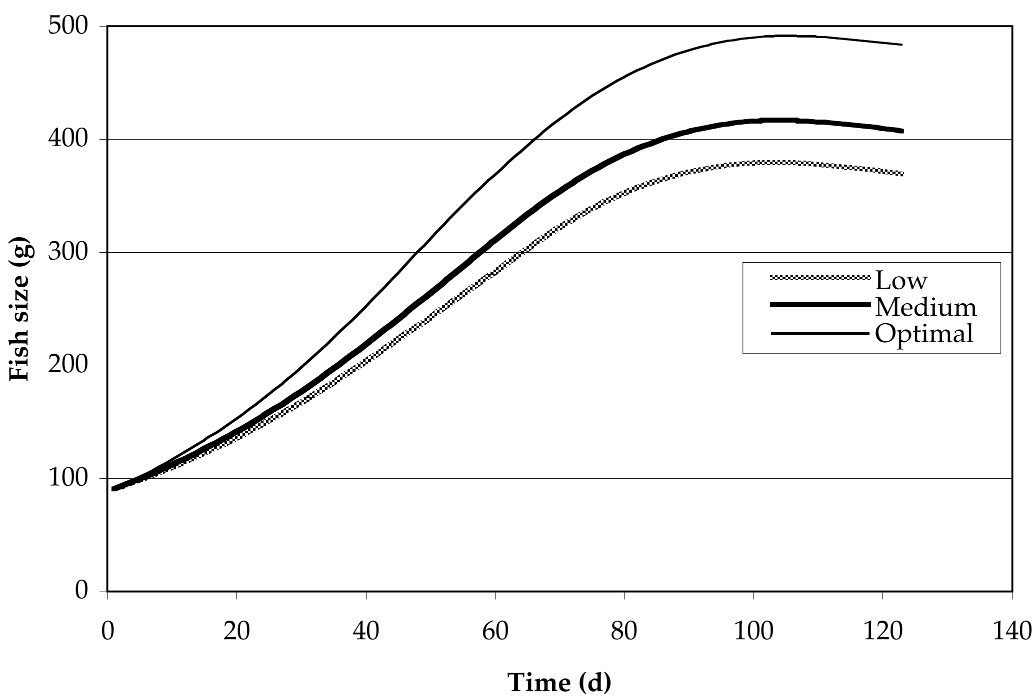

Figure 5. Growth profiles predicted by the POND© energetics model for ommon carp that received diets with low (20%), medium (25%), and optimal (30%) protein contents.

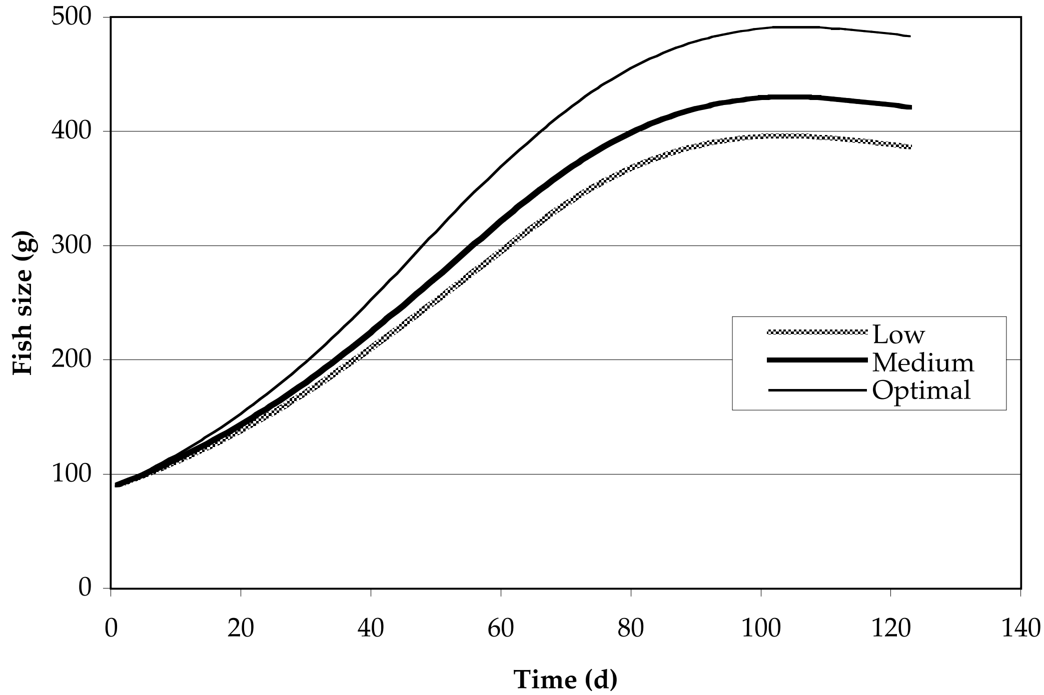

Figure 6. Growth profiles predicted by the POND© energetics model for common carp that received diets with low (2.0 kcal g^{-1}), medium (2.5 kcal g^{-1}) and optimal (3.1 kcal g^{-1}), gross energy contents.

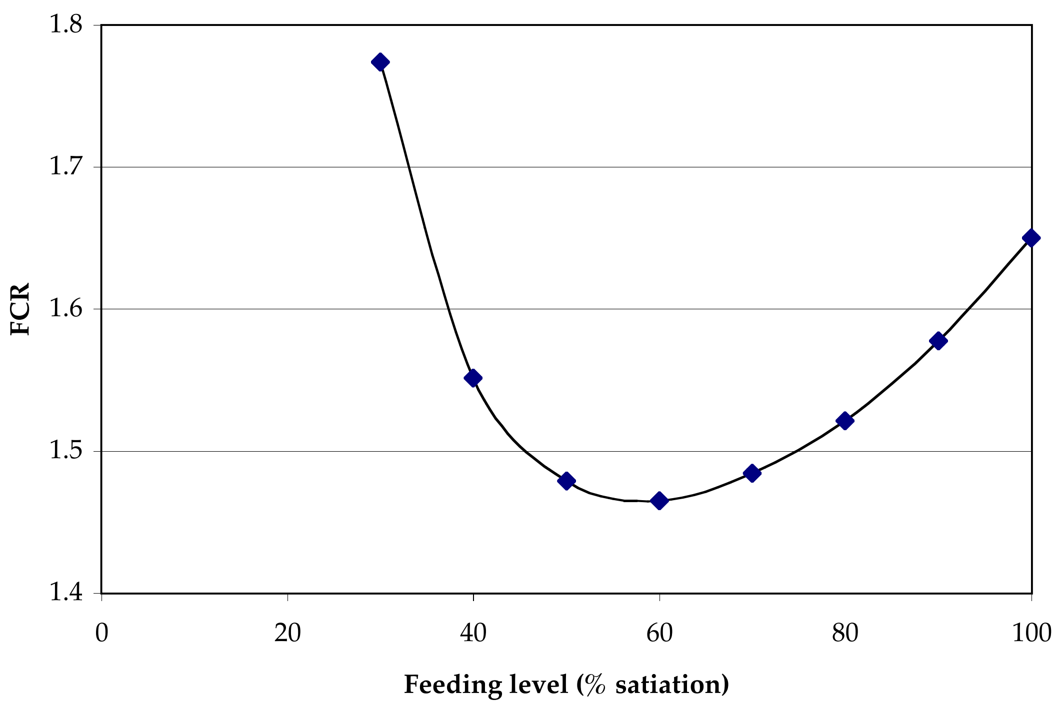

Figure 7. Relationship between the food conversion ratio (FCR) and feeding level for common carp as predicted by the POND© energetics model.

its underlying processes, which have not been adequately studied in ponds. The sediment-water interface appears to influence the flux of nitrogen, organic matter, oxygen, and phosphorus in pond aquaculture systems (Schroeder and Berner-Samsonov, 1986; Boyd, 1994). Through the development of models, an opportunity exists to better understand such processes and to design experiments to test model hypotheses.

In the Thirteenth Annual Report (Nath et al., 1996), we listed state variables that were considered in the POND© models at Levels 1, 2, and 3. During the current reporting period, the process descriptions for nutrient fluxes in pond water and sediments in the POND© software were implemented. A listing of these processes for phosphorus is given in Table 2. Model calibration and testing are in progress.

Polyculture Interactions in Ponds

Polyculture has been practiced in various parts of the world for centuries. Decisions regarding species selection and estimation of appropriate stocking densities, however, are typically based on empirical experience partly because interactions among various species within the pond environment are not very well understood. We have successfully used a resource substitution model to describe theoretical relationships between Nile tilapia and phytoplankton/zooplankton growth in ponds (Bolte et al., 1995; Nath, 1996).

In order to extend the resource substitution model approach to other species (e.g., carps), particularly under polyculture conditions, it is necessary to add descriptions of other natural food resources in pond systems. It is also important to describe changes that occur in natural food uptake when artificial feed is added to a pond. In addition to phytoplankton and zooplankton as natural food resources, we have implemented descriptions for a 'bacterial' component in POND© at Level 3 (Table 2). This component is intended to reflect the heterotrophic pathway of fish food availability in pond systems.

We have also developed an iterative method (see Nath, 1996 for a complete description) to describe supplemental feed uptake under conditions where natural food is also present in ponds. An iterative method is required because the proportion of supplemental feed consumed is not known *a priori* and cannot be assumed to equal the difference between the target feeding level and the amount derived from the natural food base (the approach used at Level 1). This is because the proportion of supplemental feed in the diet is likely to be a function of fish species preference for feed, among other factors. For example, if feed is added to a pond with fairly abundant natural food (although inadequate to reach the target level), some species may preferentially consume supplemental feed, whereas others may not. In other words, the proportion of natural food in the diet of a given fish species will likely differ depending on whether feed is present or not. At the present time, we are testing the performance of the POND© Level 3 models to predict fish performance for different species in polyculture and in fertilized versus fed systems.

Macro-Level Agroecological System Analysis

We have recently commenced two efforts in this area (Decision Support Systems Research 1D of the OSU-DAST project). The first effort involves developing the capabilities of the POND© software to simulate integrated farming systems. Models will be implemented that simulate crop growth in plots adjacent to aquaculture ponds. The process descriptions of the crop model component developed by UC Davis researchers is being reviewed to determine the best approach for integrating the model in POND©.

The second effort involves integrating the POND© fish growth and water temperature models within a Geographical Information System (GIS) to assess aquaculture potential in Africa. This project, in collaboration with the FAO, is similar to the recently completed Latin American project (Kapetsky and Nath, 1997). Presently, FAO personnel are using the POND© temperature model to make temperature projections and the recently refined fish growth models to project crop output under subsistence and commercial farming scenarios for Nile tilapia, common carp, and African catfish across the African continent.

In addition to fish yield data, Decision Support Research Study 1D will consider economic and production factors, including water requirements, urban market potential, potential for farm gate sales, availability of agricultural by-products as feed/fertilizer input, and engineering and terrain suitability for pond construction. Results from the GIS study are expected to be useful for PD/A CRSP personnel involved with the development and

Table 2. A summary of process descriptions for phosphorus flux as implemented in the three POND© modeling levels. Source and sinks affecting bacterial biomass in ponds are also indicated. Processes directly manipulated by management practices are italicized.

Variable	Model Level	Sources	Sinks
WATER-COLUMN PHOSPHORUS (P)	1, 2, 3	*Influent water*	*Effluent discharge*
Total-P	2, 3[b]	Fish respiration + excretion	Non-flow related volume changes[a]
Dissolved Inorganic-P	1	Wasted feed	Phytoplankton uptake
		Phytoplankton respiration + death	Bacterial uptake
		Zooplankton respiration + death	Sediment sinks/sources[a]
		Bacterial respiration + death	Miscellaneous sinks/sources[a]
		Fertilization	
Inorganic-P	3	Mineralization	
Organic-P	3		Mineralization
SEDIMENT-P	2, 3	Supply of water column material:	Water-column sinks/sources[a]
Total-P	2, 3[b]	From fish excretion, wasted feed, and phytoplankton, zooplankton and bacterial death.	
Sediment Inorganic-P	3	Mineralization	
Sediment Organic-P	3		Mineralization
BACTERIA	3	*Influent water*	*Effluent discharge*
		Growth	Non-flow related volume changes[a]
			Respiration and death
			Zooplankton consumption
			Fish consumption

[a] Can be either a source or a sink.
[b] Calculated from concentrations of inorganic and organic forms at Level 3.

implementation of regional planning studies for sub-Saharan Africa.

Anticipated Benefits

POND©, providing a powerful framework for analyzing the dynamics of warmwater pond systems, has been of primary benefit to technical users. The development of simpler user interfaces to assist in task completion in POND© will allow the software to serve a broader audience. Similarly, improvements in the algorithms used on POND© makes it more broadly useful and accurate in the development of more optimal management strategies and facility plans.

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Application of Systems Models for Evaluation and Optimization of Pond Management Practices

Eighth Work Plan, Decision Support Systems Research 1C (DSSR1C)

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Introduction

One of the primary uses of aquaculture models is for the comparison of different methods of pond management in terms of the effects on fish yields, the economic efficiency of the production system, and the efficiency of resource use. Pond aquaculture models may thus provide opportunity to optimize production technology. In this report, we discuss the application of models developed by OSU-DAST researchers relevant to PD/A CRSP fertilization strategies and the optimization of feed application rates. These two application areas of the OSU-DAST models are different in terms of the problem scope and implications of model outcomes. Therefore, each application area is discussed separately in this report.

PD/A CRSP Fertilization Strategies

Based on PD/A CRSP research conducted over several years, two broad categories of fertilization strategies can be identified: "fixed input" and "responsive." The "fixed input" strategy is more prevalent and involves weekly additions of fertilizers at fixed rates. Recommended fixed input rates for individual CRSP sites have typically evolved over time on the basis of successive experiments that compared different rates of nitrogen (N) and phosphorus (P) additions to ponds. The second category of PD/A CRSP fertilization guidelines, collectively referred to as "responsive" strategies, involves assessment of ambient pond water conditions prior to estimating pond nutrient needs. These strategies include fertilization guidelines generated by computer models following measurements of pond nutrient concentrations (Lannan, 1993; Nath, 1996) and bioassays (Knud-Hansen and Guttman, in prep; Hopkins and Knud-Hansen, in press).

Fixed input strategies require substantial up-front costs to experimentally determine appropriate fertilization rates (Hopkins and Knud-Hansen, in press). They may also be unreliable for estimating fertilizer requirements at geographically different locations (Lannan, 1993; Hopkins and Knud-Hansen, in press) and they do not adequately account for short- and long-term changes in aquaculture ponds (Nath, 1996). Variation in nutrient availability during a single culture period is an example of a short-term change and the accumulation of nutrients (particularly P), which may subsequently serve as a good nutrient source in pond sediment, is a long-term change.

Previous work has demonstrated that responsive strategies typically result in lower fertilization rates compared to fixed input strategies (Hopkins and Knud-Hansen, in press; Nath et al., 1997). Hopkins and Knud-Hansen (in press) also estimated fertilization efficiency in an experiment conducted in Thailand that compared Nile tilapia (*Oreochromis niloticus*) ponds managed under three different regimes. Fertilization guidelines developed from the bioassay method, PONDCLASS, and the traditional fixed input rates for that location were compared. Fertilization efficiency was evaluated in terms of the percentage of fertilizer N and P recovered in the harvested fish. This index is a useful way of comparing various fertilization strategies, because it also provides some indication of the amounts of N and P that may accumulate in the pond water and sediment. For instance, a recovery rate of 20% for P implies that roughly 80% of the P added in the form of fertilizers accumulated in the pond environment or was released (e.g., when ponds are drained for harvest). Such simple indices of production efficiency are particularly important for complex pond systems for which the establishment of detailed nutrient budgets is tedious and expensive (because of the need for frequent water and sediment quality measurements) and, therefore, not practical under most circumstances.

Results of an experiment conducted at the Asian Institute of Technology (AIT) provide convincing evidence regarding the efficacy of responsive fertilization strategies in terms of cost and fertilizer use efficiency (Hopkins and Knud-Hansen, in press). It is not known, however, whether similar trends occur at other CRSP locations or even for other experiments in Thailand. Therefore, the focus of this study was to undertake a comparative analysis of fixed and responsive fertilization strategies for three CRSP sites, in Honduras (El Carao), the Philippines Freshwater Aquaculture Center (FAC), and Thailand (AIT).

Data Sources

Fertilizer application rates, fertilizer composition data, and fish growth information for experiments that compared fixed input rates with fertilization guidelines generated by the use of PONDCLASS were extracted from the PD/A CRSP Central Database for all three sites mentioned above. The total amounts of fertilizer N and P added to each of the two treatments (fixed input and PONDCLASS) averaged across ponds, were estimated according to their respective application rates and fertilizer compositions reported in the Database. Recovery of fertilizer N and P in fish flesh was calculated assuming a tilapia composition of 9.5% N, 2.4% P and 76% moisture (Tan, 1971 as cited by Hopkins and Knud-Hansen, in press). Cost efficiency was estimated as the cost of fertilization per kilogram of fish produced.

An additional assumption in the fertilizer calculations for El Carao and AIT (where manure was used) was that only 50% of the total N and 75% of the total P in chicken manure becomes available in ponds following fertilizer application (Nath, 1992). Fertilizers used in the PONDCLASS experiments at El Carao included chicken manure (CM), urea, and diammonium phosphate (DAP), which cost 0.016, 0.28 and 0.33 US$ kg^{-1}, respectively (Molnar et al., 1996). At AIT, available fertilizers were CM, urea, and triple superphosphate (TSP), with respective costs of 0.01, 0.27 and 0.47 US$ kg^{-1} (Molnar et al., 1996). At FAC, urea and a N:P:K (16-20-0) mixture were the fertilizers used in the PONDCLASS experiments, with respective costs of 0.29 and 0.30 US$ kg^{-1} (Hopkins, K., personal communication).

Results and Discussion

Total N and P additions, net fish yields, and fertilization efficiency in terms of nutrient recovery and costs for the fixed and responsive fertilization strategies are summarized in Table 1. Data from Hopkins and Knud-Hansen (in press) are also presented in this table for comparative purposes.

With the exception of the 1994 experiment in Thailand, responsive fertilization strategies were three to seven times more efficient in terms of P recovery compared to the corresponding fixed input strategies. This translated into P application rates that were 3.5 to 5 times lower than the commonly recommended fixed inputs at a particular location. Differences in the efficiency of N recovery were not as striking (Table 1). However, with the exception of the Honduras experiment, efficiencies of N recovery in the responsive strategies were slightly higher than, or comparable to, the fixed input strategies.

Net fish yields for the fixed input treatments were in general higher than the responsive strategies' yields (with the exception of the Philippines) (Table 1). However, in terms of practical fish production, it is the cost efficiency (i.e., fertilizer costs per unit of fish produced) and not the highest yield that is important. When this index of comparison is used (Table 1), responsive fertilization strategies were 1.5 to 3 times more efficient than fixed input strategies for the experiments conducted in the Philippines and Thailand. For Honduras, the PONDCLASS and fixed input strategies were comparable in terms of cost efficiency.

In the 14th Annual Report (Nath et al., 1997), we indicated that substantial changes had been made to the PONDCLASS fertilization model based on results of the Global Experiment for the Seventh Work Plan. This new approach has been implemented in the POND© software. Comparisons among the fixed input, PONDCLASS, and POND© fertilization guidelines were undertaken for CRSP sites in Honduras, the Philippines, and Thailand (see Nath, 1996 for details). Results for the Philippines are presented in Figure 1, where it is evident that fertilizer N recommendations obtained by the use of POND© are more conservative than

Table 1. A comparison of the total fertilizer inputs over the experimental period, fertilization efficiency use (i.e., fertilizer N and P recovered in fish), net fish yields (NFY), and cost efficiency for fixed and responsive fertilization strategies (PONDCLASS and Bioassay) at three different CRSP locations.

Site	Regime	Inputs ($kg\ ha^{-1}$)		% Recovered in Fish		NFY ($kg\ ha^{-1}\ yr^{-1}$)	Cost Efficiency ($ per kg fish)
		N	P	N	P		
El Carao, Honduras[a]							
	Fixed	522	216	11.8	7.2	6975	0.19
	PONDCLASS	609	42	7.8	28.7	5425	0.20
FAC, Philippines[a]							
	Fixed	464	94	5.2	6.5	3168	0.51
	PONDCLASS	534	26	4.7	24.0	3259	0.35
AIT, Thailand							
1992-93[b]	Fixed	493	255	9.8	4.8	6463	0.42
	PONDCLASS	408	54	8.3	15.6	4491	0.15
	Bioassay	408	32	9.2	29.4	5022	0.20
1994[a]	Fixed	588	147	7.7	7.8	4781	0.35
	PONDCLASS	426	141	10.4	7.9	4681	0.20

[a] Data extracted from the PD/A CRSP Central Database.
[b] Data from Hopkins and Knud-Hansen, in press.

those for PONDCLASS (N addition tended to be excessive). Both POND© and PONDCLASS generate fertilizer P recommendations that are much lower than the traditional fixed input rate used in the Philippines (Figure 1).

Results from the comparative analysis of fixed and responsive fertilization strategies clearly demonstrate that the latter are typically much more cost efficient. The higher percentage of nutrients recovered in fish flesh indicates that the use of responsive fertilization strategies will likely lead to reduced accumulations of nutrients (particularly P) in the pond environment. In terms of P application rates, it appears that CRSP ponds managed using fixed input strategies are receiving much more fertilizer P than is necessary for high algal and fish production. It is not clear whether this finding is due to P that has accumulated in pond sediments over the past few years of fertilization (and is now being returned to the water column) or whether there has always been an over-supply of P from the fixed input strategies. Both possibilities merit further investigation, because excessive nutrient addition is economically wasteful and may have undesirable environmental consequences. In any event, our analysis suggests that there is a need to re-evaluate the present rates of N and P additions recommended for each of the sites tested. It is also necessary to conduct field experiments to test the guidelines generated by the refined POND© fertilization model at different CRSP locations so that the resulting information can be used to fine-tune the responsive fertilization strategy.

One drawback of responsive fertilization strategies is that they require routine (weekly or biweekly) assessment of fertilizer needs (either in the form of water collection and incubation, as in the bioassay method, or water quality analysis, as in the computerized approaches). It may also be necessary to adjust fertilizer application rates on a pond-by-pond basis. Weekly or biweekly assessments are difficult to circumvent because the very strength of responsive strategies is that they modify fertilization rates in accordance with changes in pond water quality. However, it may be possible to assess fertilizer needs on a monthly basis and use the fertilizer recommendations obtained at that point for the following four weeks (assuming that fertilizer addition occurs once a week). This can be accomplished by examining the sensitivity of responsive strategies to different time intervals of water quality assessment in an experimental setting.

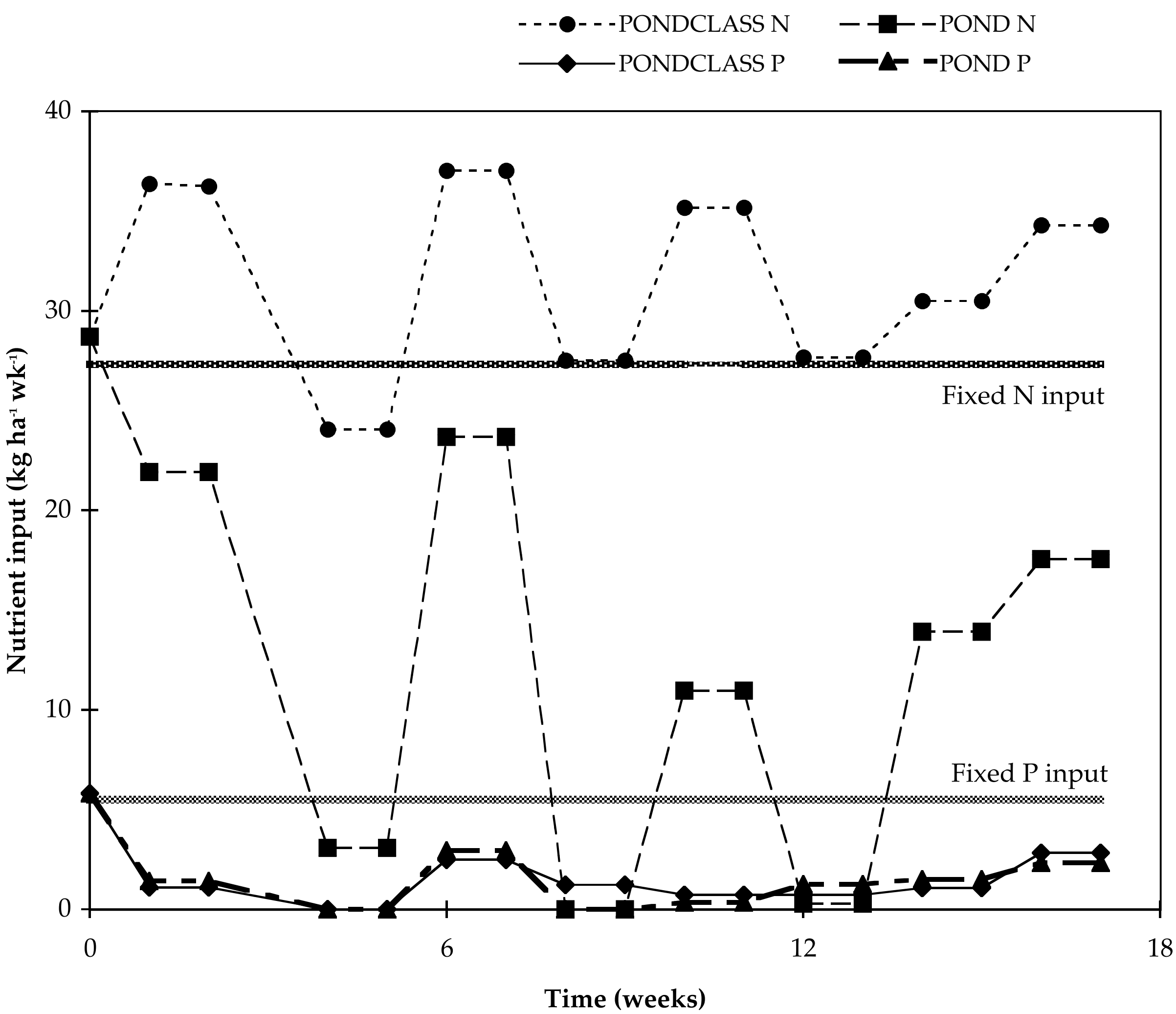

Figure 1. Weekly nutrient N and P inputs for experiments at the Freshwater Aquaculture Center (FAC) in the Philippines that correspond to fixed input (straight lines) and PONDCLASS fertilization rates. Simulated rates generated by the use of POND© are also shown.

The adjustment of fertilization application rates for individual ponds required with responsive fertilization strategies may not be a significant drawback for small, tropical ponds for which labor is relatively inexpensive and fertilizer is manually applied. However, for highly mechanized operations such as the baitfish industry in the US, this drawback assumes significant proportions because of the following reasons (Stone, N., personal communication):

- Labor costs are generally high;
- Fertilizers are typically applied by the use of mechanical devices which do not easily lend themselves to custom mixes of N and P for individual ponds; and
- The cost of fertilizers in the US is relatively low compared to other variable costs.

We are currently exploring the possibility of developing an expert system which takes into account geographical information (e.g., seasonal temperature and solar radiation profiles) and general pond characteristics (alkalinity, soil type, pond history, etc.) to generate preliminary estimates of fertilization rates in conjunction with the POND© models. These estimates can subsequently be fine-tuned under field conditions. Such an expert system may also be useful in providing estimates of the upper limit of algal productivity for different geographic locations. This information could perhaps be used together with the bioassay technique under field conditions to predict fertilizer application rates that are appropriate for the site under consideration.

Optimization of Feed Application Rates

Feeds often represent the single largest component of variable costs to an aquaculture facility. Therefore, estimating the minimum amount of feed required to reach a specified target size within an acceptable period of fish culture is likely to be beneficial to pond managers, planners, and researchers.

Development of the Optimization Methodology

Bolte and Nath (1996) demonstrated the use of an adaptive, non-linear search technique (genetic algorithms or GAs) to automatically calibrate the POND© fish growth model. We are currently experimenting with GAs as an optimization tool in POND© for estimating feed requirements.

The goal of the POND© feed optimizer is essentially to generate feeding schedules (expressed on a percent satiation basis) that enable a user-specified, target fish size to be reached with the minimum amount of feed. GAs involve the evaluation of populations of solutions based on principles of natural selection (i.e., individuals with higher fitness have a higher probability of being selected into the next generation) over a specified number of generations, until a highly evolved population results (see Holland, 1975; Michalewicz, 1992 for further details). The final population consists of suitable solutions to the problem on hand.

In the POND© feed optimizer, an "individual" (feeding schedule) corresponds to a list of feeding levels that are expected to be changed every four weeks, for the entire culture period. Thus, for a culture period that lasts 28 weeks, a single "individual" in a population consists of seven monthly feeding levels. The "fitness" of an "individual" is the total amount of feed added over the culture period, with a higher fitness level corresponding to lower amounts of feed.

The search procedure consists of the following steps:

1. Create an initial population of individual feeding levels (typically 20).
2. POND© automatically executes fish growth simulations with this population.
3. Evaluate the 'fitness' of individuals in the population.
4. Generate a new population using 'crossover' (exchanging feeding levels between two individuals) and 'mutation' (randomly changing one or more feeding levels in an individual) operators.
5. Repeat steps two through four above until the specified number of generations is reached (typically 15). The individual with the greatest fitness represents the feeding strategy that requires the least amount of feed for fish to attain the specified target size.

Currently, the feed optimizer in POND© is being tested and evaluated. Preliminary trials were conducted wherein feed requirements were estimated for the culture of the African catfish (*Clarias gariepinus*) under two conditions: feeding to full satiation and feeding according to the optimal schedule generated by the use of the GA-based optimizer. In the latter, it was assumed that acceptable feeding levels ranged from 75 to 100% satiation. Stocking densities were two fish m^{-2} and fish weight was 50 g. Fish were assumed to be stocked on January 1 and harvested no later than April 30. The target fish weight was set at 400 g. Daily mortality was assumed to be 0.1%. Feed composition was assumed to be as follows: moisture content (10%), gross energy (3.6 kcal g^{-1}), and protein level (30% on a dry matter basis).

Optimization Results and Discussion

Under simulation conditions of satiation feeding, the target fish weight was attained in a 100-d culture period, whereas feeding at rates suggested by the GA-based feed optimizer resulted in the target weight being reached in 117 d. Production parameters are summarized in Table 2. Net fish yield under satiation feeding was predicted to be higher than that for fish fed according to the schedule generated by the GA. This is because the number of fish at harvest as predicted by POND© was higher for satiation feeding (Table 2), a result of the shorter culture period and the assumption of a uniform daily fish loss due to mortality.

Feeding rates (expressed as % satiation) corresponding to the best feeding solution obtained by the GA (Figure 2) indicate that the optimizer recommended rates that increased according to fish weight. The rate of increase also

Table 2. A summary of African catfish (*Clarias gariepinus*) production parameters for POND© simulations wherein fish were fed to satiation and according to the "optimal" feeding schedule generated by the GA.

Feeding Schedule	Culture Duration (d)	Net Fish Yield (kg ha^{-1})	Feed Requirements (kg ha^{-1})	Food Conversion Ratio
Satiation	100	6103	9400	1.55
Optimal	117	5905	8857	1.49

increased with time. Because comparative results under actual pond management conditions are not available, it is difficult to judge whether such results are realistic. More likely than not, it would appear that the use of very high feeding rates at high fish biomass levels would adversely affect growth because of the effects on water quality. These effects are not captured in the present version of the feed optimizer, but it may be possible to introduce them in the form of 'penalty functions' which reduce the fitness of individuals that require high feeding rates when fish biomass is high. The effect of such penalty functions would reduce the probability that these individuals enter a new generation of the GA-based optimizer.

Overall feed requirements generated by the GA-based optimizer were about 550 kg less than those predicted under satiation feeding conditions (Table 2). Although this difference potentially represents substantial savings (depending on local feed costs), model outputs must also be evaluated in terms of the operating costs that are required to hold fish for the additional 17 days and the value

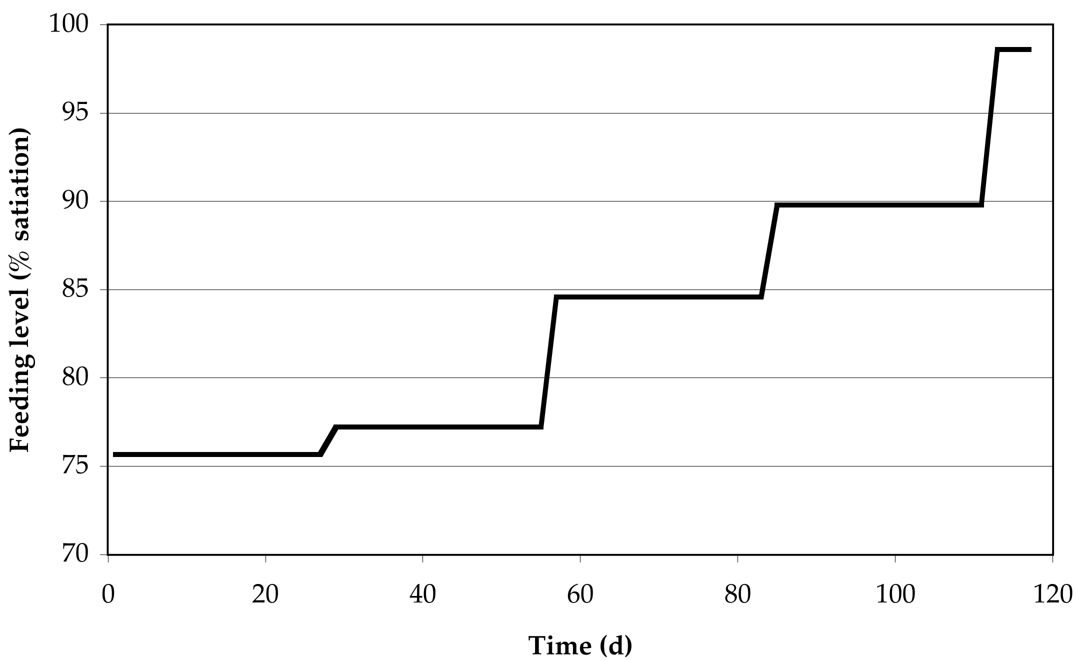

Figure 2. Feeding levels for the optimal solution generated by the GA-based feed optimizer in POND©. The levels reflect feeding rates that are fixed for four week intervals.

of the higher yield predicted under satiation feeding conditions. In other words, optimizing feed usage *per se* may not generate outcomes that are economically optimal for the overall enterprise. This suggests that similar types of model-based optimization studies should perhaps take into account the overall costs and benefits of production. This can be accomplished within the GA-based optimization framework by modifying the 'fitness' function to reflect such costs and benefits. As an example, minimization of the variable cost of producing one unit of fish may be an alternative fitness function. Our future work will focus on this area of facility-level optimization.

The other area of research that we believe would be beneficial to the overall CRSP effort of developing efficient pond aquaculture systems is to continue to more closely link modeling with field research efforts. The benefits of comparing model-recommended guidelines to those traditionally used at the three different CRSP sites are clearly demonstrated for fertilized systems in this report. Similar benefits can be expected if the newer POND© models/optimization techniques and their outputs are subjected to comprehensive testing in the field.

Anticipated Benefits

Optimization of feed and fertilizer additions supporting pond aquaculture production enhances the profitability of pond facilities and reduces excess resource consumption. Models such as POND© perform a rational analysis of feed and fertilization strategies to determine the effect of different management strategies which consequently lead to the development of optimal management regimes. Such analyses benefit producers and planners in developing management regimes which provide the maximum benefit to the facility, in terms of enhanced profitability, and to the environment, in terms of reduced effluent discharge of unutilized production inputs.

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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

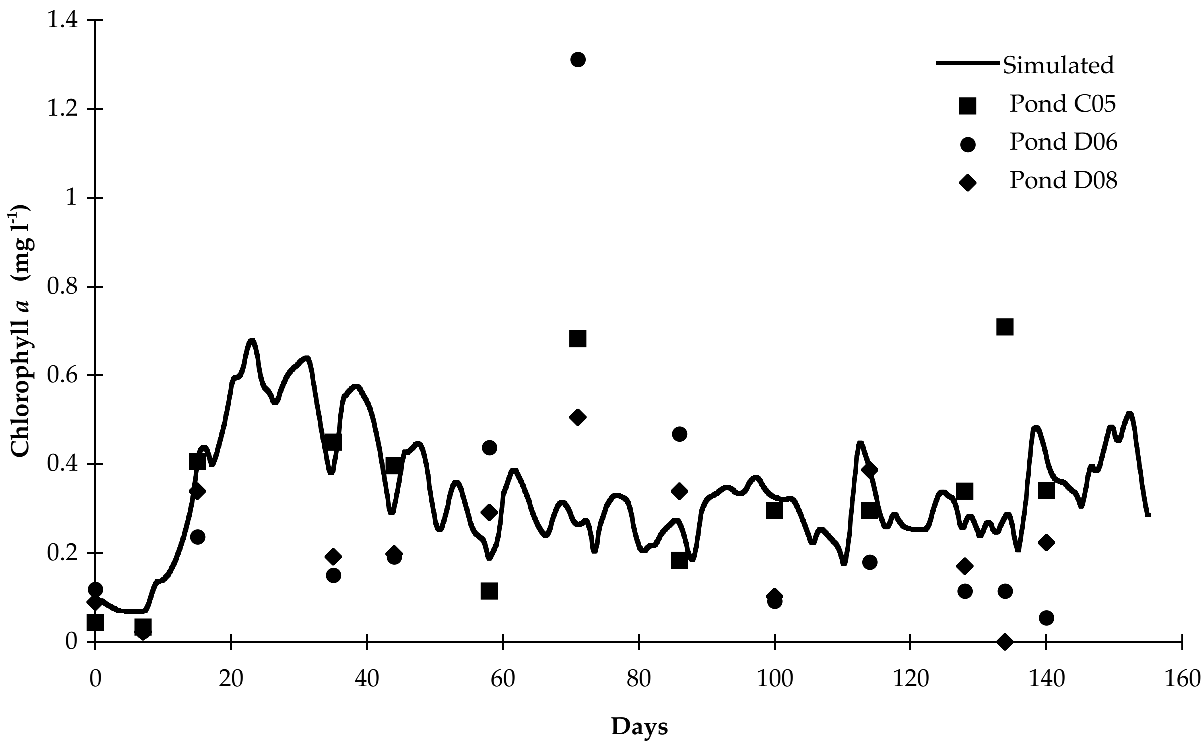

Figure 1a. Simulated chlorophyll *a* concentrations and observed values from three experimental ponds.

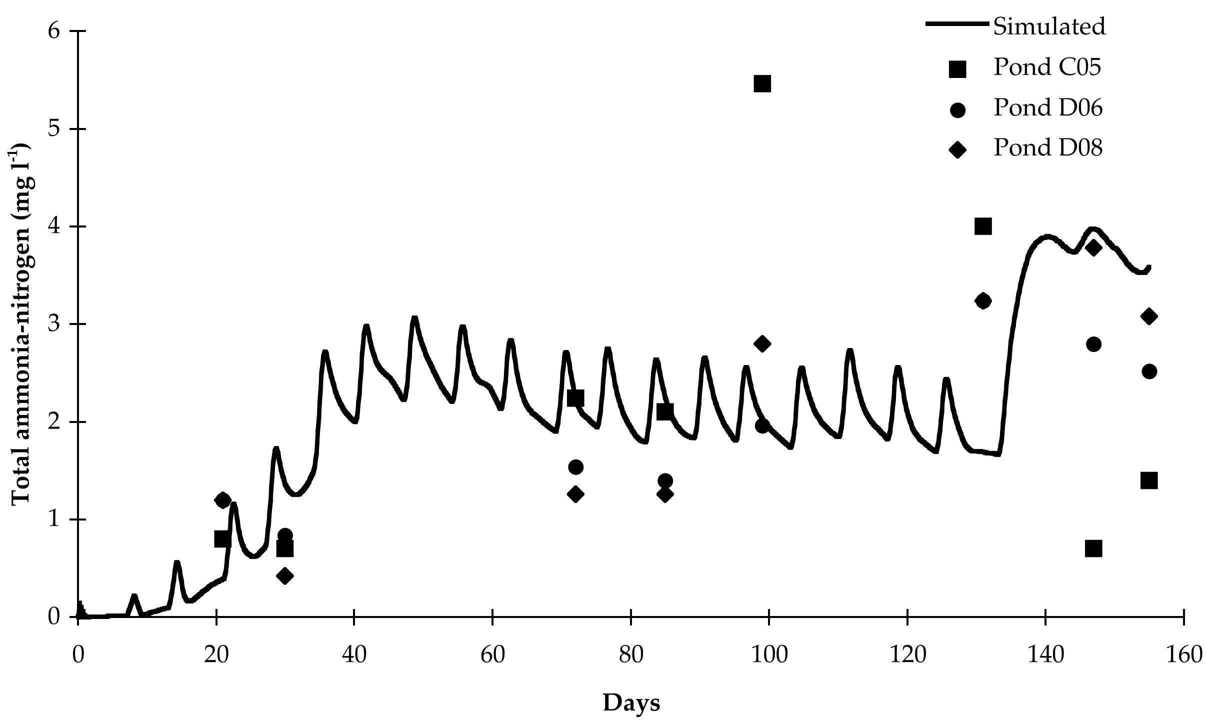

Figure 1b. Simulated total ammonia-nitrogen concentrations in the water column and observed values from three experimental ponds.

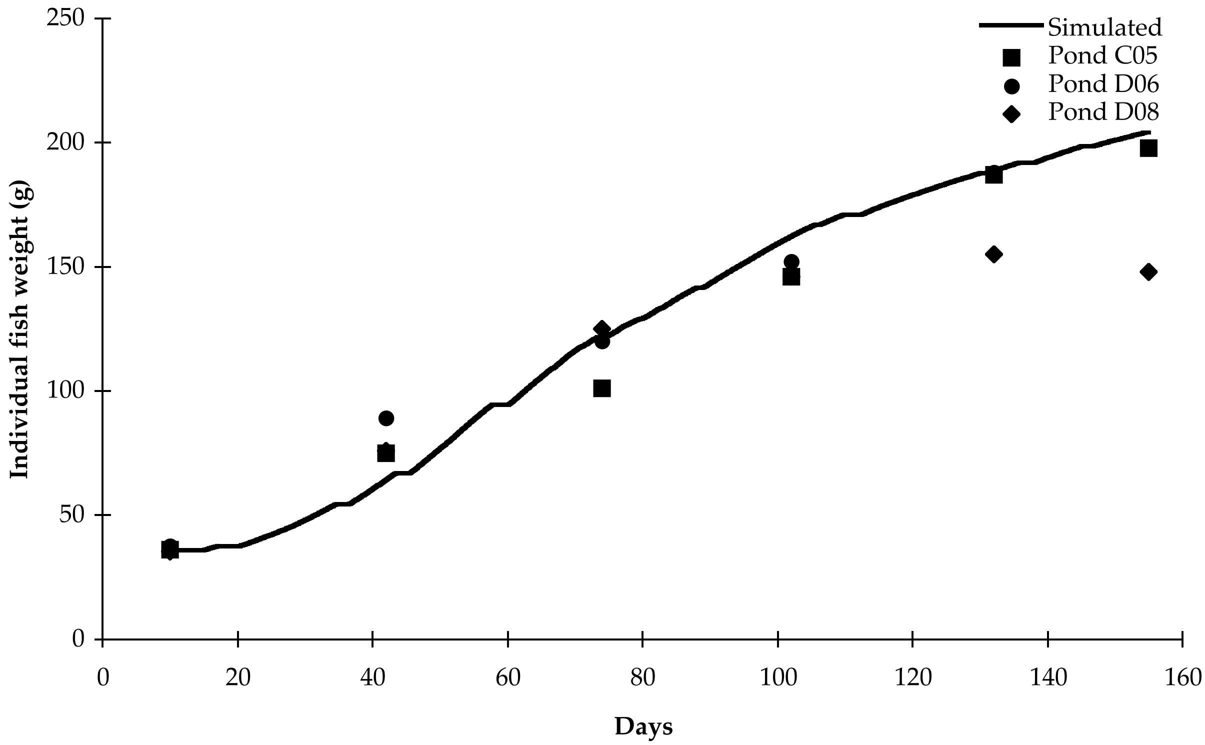

Figure 2. Simulated weights of individual fish and weights of fish from three experimental ponds.

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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Aquaculture Pond Modeling for the Analysis of Environmental Impacts and Integration with Agriculture: Modeling of Temperature, Dissolved Oxygen, and Fish Growth Rate in Stratified Ponds Using Stochastic Input Variables

Eighth Work Plan, Aquaculture Systems Modeling Research 1B (ASMR1B)

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Introduction

The prediction of water temperature and dissolved oxygen (DO) in stratified fish ponds can help in managing water quality and improving fish production. A model is being developed to simulate water temperature, DO, and fish growth under the effects of random weather variables. Values for solar radiation, air temperature, and wind speed are generated using stochastic methods. The water column is considered to be uniform in the horizontal plane but not in the vertical, where three distinct layers are considered: surface, mid-depth, and bottom. Diurnal water temperature, DO, and other related water quality and biological variables are simulated for these three water layers.

The model consists of several inter-related components: the generation of values for weather parameters and the simulation of water temperature, DO concentration, and fish weight. The weather values are generated using stochastic methods based on statistical analysis of the local weather data. The water temperature and DO models have been constructed based on an initial deterministic model for simulating water temperature and DO over periods of approximately 24 hours (Losordo, 1988; Culberson, 1993). The fish growth rate simulation is adapted from the model developed by Bolte et al. (1995) and modified by Jamu and Piedrahita (1997).

Modifications and development of the model during the reporting period have been concentrated in the following areas:

1. Improvement of the way in which phytoplankton respiration is quantified;
2. Modification of the model so that pond water exchanges can be considered;
3. Consideration of different types of organic matter with varying rates of decomposition and oxygen consumption; and
4. Modification of the fish growth model to allow for the consumption of different types of foods.

Developments in each of these areas are described below.

Phytoplankton Respiration

Phytoplankton dynamics tend to dominate the oxygen cycle in most aquaculture ponds. Accurate prediction of the rates of phytoplankton growth and respiration is essential in obtaining water quality simulations that closely match the reality of aquaculture pond behavior. The rates of oxygen production and consumption by phytoplankton vary as functions of environmental conditions and other parameters. The phytoplankton primary production rate takes into account the effects of light intensity, ammonia nitrogen concentration (as a source of inorganic nitrogen), water temperature, and the concentration of chlorophyll *a*. Phytoplankton "consumption" terms, other than the phytoplankton respiration term, in the mass balance calculations are: phytoplankton death, grazing by fish, and sinking or settling of phytoplankton to the sediment. These consumption terms are modeled using a first order model with constant specific rates. However, in the current model, the concentration of DO and water temperature have been included in the equations used to simulate the phytoplankton respiration rate:

$$K_{chla} = k_{sp} f(t) \frac{C}{k_c + C} \quad (1)$$

where

K_{chla} = phytoplankton respiration rate (1/h),

k_{sp} = specific reference phytoplankton respiration rate at 20°C (1/h),

$f(t)$ = $\theta^{(T-20)}$ temperature dependence (unitless),

C = oxygen concentration, (mg l^{-1}),

k_c = half saturation constant of oxygen respiration (mg l^{-1}).

Pond Water Exchange

In most PD/A CRSP fish ponds, water is added to maintain the water level and to make up for losses due to evaporation and infiltration, but there is no effluent during normal pond operation. However, water exchange in fish ponds may have a significant impact on water quality. Similarly, the effluent from fish ponds may introduce significant amounts of nutrients into receiving waters. The model under development was modified to include water inflow and outflow terms in the energy and mass balance calculations for temperature and water quality, respectively. The modifications make it possible to use the model to estimate water quality changes in a pond caused by water exchange and to quantify the quality of the effluent and possible nutrient releases to the environment.

In the current version of the model two assumptions are made regarding water exchange. The first assumption is that the water influent and effluent flow into and out of the pond surface layer. The second assumption is that the water inflow is well mixed with pond water in the surface layer, and that there are no temperature and DO differences within that layer. The equations for the energy balance and DO mass balance are presented in a simplified form to illustrate the inclusion of the influent and effluent terms. The energy change due to the water inflow and outflow is expressed as:

$$\frac{dH_E}{dt} = H_{in} - H_{out} \quad (2)$$

$$H_{in} = Q_{in} C_p \rho T_{in} \quad (3)$$

$$H_{out} = Q_{in} C_p \rho T_{out} \quad (4)$$

where

$\frac{dH_E}{dt}$ = rate of heat flux due to water exchange through the pond (kJ h^{-1}),

Q_{in} = rate of water inflow (m^3 h^{-1}),

C_p = water heat capacity, (kJ kg^{-1} °C^{-1}),

ρ = water density (kg m^{-3}),

T_{in} = temperature of the influent water (°C),

Q_{out} = rate of water outflow (m^3 h^{-1}),

T_{out} = temperature of the effluent water (°C).

The DO change caused by the water exchange can also be presented in a simplified form:

$$\frac{dC_E}{dt} = DO_{in} - DO_{out} \quad (5)$$

$$DO_{in} = Q_{in} C_{in} \quad (6)$$

$$DO_{out} = Q_{out} C \quad (7)$$

where

$\frac{dC_E}{dt}$ = DO rate of change caused by the water exchange (g h^{-1}),

C_{in} = oxygen concentration in the inflow (g m^{-3}),

C = oxygen concentration in the fish pond (g m^{-3}).

Equations (2) and (5) may be applied to a different water layer (middle or bottom layers) if the location of the influent or effluent is such that water is being added or removed from those layers. Although heat capacity is a function of temperature, it is assumed to be the same for the influent and effluent because the heat capacity difference between the two waters is negligible compared to other changes and processes in the pond.

Organic Matter Decomposition

Fish ponds may receive various organic and inorganic fertilizers and feeds. The types, amounts, and application methods of organic fertilizers and feeds affect the concentrations of DO significantly according to the decomposition rate of organic matter introduced. In the previous version of this model (Lu and Piedrahita, 1997), oxygen consumption in the water column due to organic matter decomposition was assumed to be a function of water temperature only. This approach did not consider the changes of the concentrations of various forms of organic matter, such as fertilizers, dead phytoplankton, uneaten fish feed, etc. Although the oxygen consumption due to nitrification was separated from the water column respiration, and ammonia concentration is simulated using mass balances, the ammonia nitrogen reduction via the decomposition of organic nitrogen could not be predicted accurately due to the non-inclusion of the dynamics of organic matter in the model.

In the past, fish ponds at the PD/A CRSP research sites have been fertilized with different types of fertilizers, and the model has been modified such that fertilizer differences can be taken into account. The model to simulate organic matter decomposition has been adapted from that developed by Jamu and Piedrahita (1997). Three types of organic matter components are considered based on their decay rate: easily decomposed material with a high rate of decomposition, material with a moderate rate of decomposition, and stable organic matter having a low decomposition rate. In this model only two decomposition rates are included since the stable material is considered to create a negligible oxygen demand. The two types of organic material considered are:

1. The easily decomposed organic matter, such as carbohydrate and proteins; and
2. Organic matter with a moderate rate of decomposition, such as cellulose and lignin.

The average decomposition rate of a given material can be estimated based on its approximate composition and concentration of carbohydrates and crude protein (easily biodegradable), and cellulose and lignin (moderately biodegradable). The organic matter included in the current model comprises fertilizers, fish fecal material, and dead phytoplankton. The concentration for each type of organic matter is simulated using mass balance equations.

Uptake of Various Feed Types

Most PD/A CRSP experiments have not used artificial food in the past; however, this trend is changing in current and future experiments. The change is in part a result of shifts in how pond aquaculture is viewed and carried out throughout the world. As a result, the pond model has been modified such that artificial food and various natural feed sources can be considered. The model for the simulation of multiple feed uptake has been adapted from the model developed by Jamu and Piedrahita (1996), which was in turn based on the work of Bolte et al. (1995). Feed uptake is considered to be dependent on the concentration of the various feed sources and on the preference of fish for a particular feed type. The assumption made is that fish take the preferred feed until it can not meet their intake demand, at which point a substitute feed will be taken. In the current model, the artificial feed is the preferred feed and is consumed by the fish whenever it is available. Other possible food sources considered in the model are phytoplankton and detritus or particulate organic matter.

Simulation Results

The model was tested using data from the PD/A CRSP Rwanda site. The model was run 20 times for a simulation period of 146 days. The hourly solar radiation, air temperature, and wind speed were generated based on the statistics of the 1986 to 1991 data from the Rwanda site. The input variables used were from ponds CO5, DO6, and DO8, Work Plan 4 , Experiment 3. The ponds were fertilized using chicken manure, green grass, and urea.

The average, maximum, and minimum values of water temperature and DO at the three pond depths after 20 model runs are listed in Table 1. The simulated values indicate a high degree of stratification, which is probably caused by the high light extinction coefficient and high phytoplankton concentration. The frequency distributions of DO for the surface, middle and bottom layers are shown in Table 2. The simulated chlorophyll *a* values are compared to the measured data in Figure 1. There are few measurements of chlorophyll available in the data set, and there is very high variability in the data. For example, three ponds (CO1, DO6, and DO8) undergoing the same

Table 1. Simulated temperature and DO for surface, middle, and bottom layers. The values represent means of hourly values obtained for the 146-day simulations.

Variables	Average	Minimum	Maximum
TEMPERATURE (°C)			
Surface	16.77(1.25)	13.49(0.96)	24.00(2.35)
Middle	19.33(0.59)	16.62(0.87)	18.67(0.50)
Bottom	18.67(0.50)	16.32(0.80)	20.87(0.65)
DO (mg l^{-1})			
Surface	3.65(2.96)	0.27(0.64)	9.99(7.42)
Middle	1.06(1.0)	0.07(0.41)	3.19(2.34)
Bottom	0.2(0.44)	0.02(0.37)	0.94(1.12)

Standard deviations in parentheses.

Table 2. Percent frequency distribution of DO for surface, middle, and bottom layers. The numbers indicate the fraction of the total number of hours simulated during which the DO was within the ranges indicated.

DO (mg l^{-1})	Surface	Middle	Bottom
0-1	12.99	23.29	68.29
1-2	21.03	42.24	26.28
2-3	11.13	15.04	4.37
3-4	9.79	10.30	0.71
4-5	7.65	4.51	0.09
5-6	5.54	1.94	0.03
6-7	4.42	1.28	0.03
7-8	4.54	0.57	0.03
8-9	4.08	0.49	0.17
9-10	3.42	0.11	0.00
10-11	2.45	0.06	0.00
> 11	12.96	0.17	0.00
Total	100.00	100.00	100.00

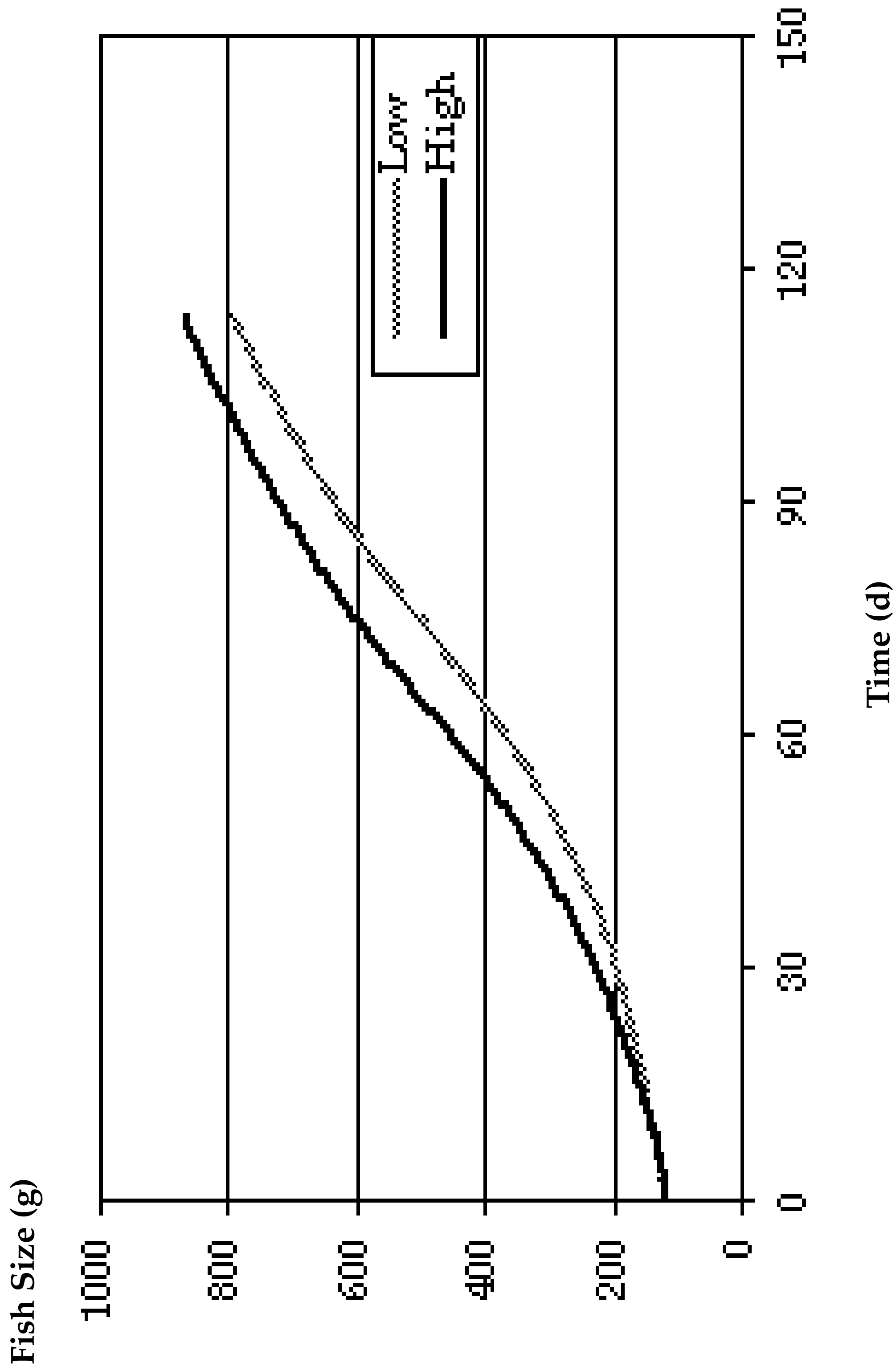

Figure 1. Simulated and measured chlorophyll *a* values for three replicate ponds (CO5, DO6, and DO8).

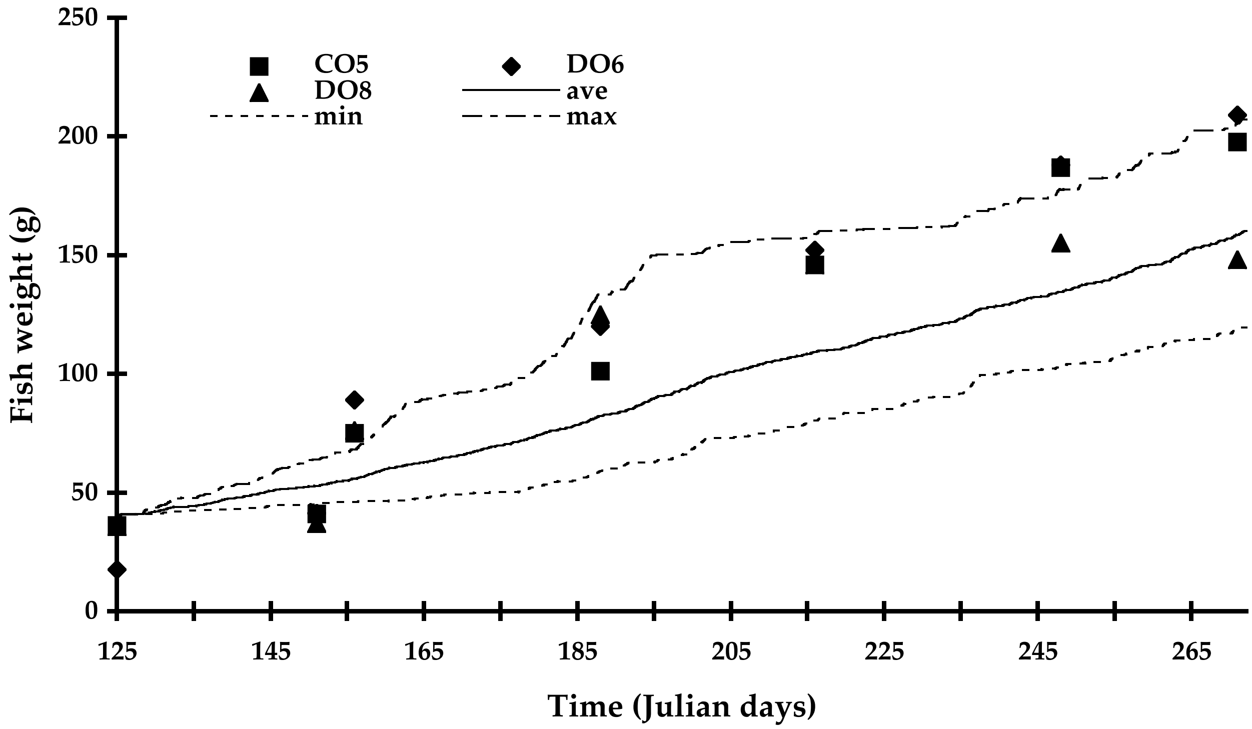

Figure 2. Simulated and measured average fish weights for three replicate ponds (CO5, DO6, and DO8).

treatment had chlorophyll *a* concentrations of 709, 114, and 0 mg m^{-3}, respectively. Figure 2 shows a comparison of the simulated average individual fish weight with the measured data indicating good agreement between the model and the data. Figure 2 also illustrates the widening of the probable range of expected fish sizes as the duration of the grow-out period is increased.

Anticipated Benefits

The model facilitates the prediction of ranges of water temperature, dissolved oxygen, and fish growth rate under different treatments (feeding and fertilization regimes). The simulation results will be useful for fish pond site selection and management.

Future Directions

Improvements to the model are still needed in the following areas: the ammonia concentration effects on phytoplankton growth, and fish mortality rate due to the variability of the water quality. The model will be calibrated and validated using PD/A CRSP data from different treatments and/or sites.

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Assessing the Human Capital Impacts of the PD/A CRSP: A Conceptual Framework

Eighth Work Plan, Adoption and Diffusion Research 1 (ADR1)

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Introduction

The Pond Dynamics/Aquaculture Collaborative Research Support Program (PD/A CRSP) functions to increase the use of aquaculture in developing nations. The project's mission is to improve the sustainability of aquaculture production systems of indigenous, noncommercial fish farmers so that food supply and human nutrition are enhanced. An implicit goal in the CRSPs mission is to improve the nutritional levels of the rural poor in collaborating nations. It will accomplish this through establishment of fish ponds on individual farms or through improvement of commercial fish farms. Another goal is to give small- to middle-sized farms an alternative cash crop, avoiding dependence on a single agricultural crop for survival. Large farms may use PD/A CRSP results to increase the overall supply of fish, provide fingerlings for area farmers, and increase export earnings for the nation. Fish farming can be a full-time livelihood for individuals with the time and resources to pursue the enterprise. For many others, aquaculture is a means to diversify a farming system, utilize underexploited resources, or augment family nutrition and income on an occasional basis.

One significant consequence of a development intervention like the PD/A CRSP is the human capital that is put in place to sustain the benefits of fish culture for the long-term. The aim is to train farm operators, technical personnel, and professional staff who will establish and staff farms, industrial firms, extension organizations, and research stations in the field of aquaculture. The PD/A CRSP hopes to fulfill these goals while laying the foundation for these nations to continue the work.

One aspect of the project supports graduate and undergraduate education plus non-degree training in aquaculture for students in the chosen countries. The intent is that eventually these countries will become self-sustaining, able to conduct their own research and extension programs to benefit the people within their countries. The strategy of funding students relies on those students continuing their careers in private firms, as well as public research or extension agencies. These occupations benefit the aquaculture industry in multiple ways—as farmers, commercial fishery technicians, managers, educators at the university level, researchers or extension workers.

Schuh (1989), a leader in the field of development, has observed that the students associated with programs similar to the PD/A CRSP do not always utilize their education to the benefit of the industry. For reasons unknown, the students may not be finding work in research, education, or extension after program completion. This study will endeavor to determine the extent to which this assertion is true. It will employ multiple data sources that may begin to show the private industry, research, and extension career paths followed by the students. The focus of the study will be threefold. First, to profile the social and demographic backgrounds of students associated with PD/A CRSP activities. Second, to ascertain student perceptions of the value of their education and the career aspirations that drive their endeavors. Third, to assess the extent to which developing country personnel, trained by the CRSP, remain in the aquaculture industry and to document the nature of their employment.

Context

United States policy has tended to support projects that promote the development of certain industries and countries. This is not the only government or organization to do so. Among these projects, a trend has begun to focus on developing human capital. Human capital is the cognitive ability, physical ability, and training that allows an individual to become a productive member of society. The programs that wish to improve the standard of living of persons use a strategy that impacts one or all of the aspects of human capital, theorizing that those individuals will in turn be able to aid others. In this manner, the program can eventually be phased out without fear of collapse of that aspect of society.

The objectives for human capital development through association with an aquaculture research project are often very general. Therefore, it is necessary to develop a conceptual model for comparison purposes. The expected impacts on educational institutions, the public sector, and private industry are manifold and diverse. Previous research has shown that the impacts of the PD/A CRSP are only indirectly telegraphed to farm level. The most direct impacts are, and should be expected to be, on the individuals with direct interaction and exposure to PD/A CRSP personnel and their activities.

Human Capital Development

In the human capital literature, one finds several patterns and trends. Most human capital development projects were agricultural in nature. Most approached their projects in much the same fashion—research, education at the college level, and extension services. Most articles reported their results in terms of the success of the research conducted. Some went as far as to report on the changes in the standard of living of participants. No literature reported on the results of the education aspects of their projects. No articles announced success in disseminating large amounts of information throughout the societies they aided. No article could be found that traced the knowledge from the school to the outside world.

This is what brought this proposal idea to the forefront: a need to know where the knowledge goes. Once in the head of the student, the knowledge does not stop moving. According to the ideal model for human capital development, the knowledge is passed on to others. Is it really? Alternatively, is it stagnating, going unused? Certain researchers have made their own nonscientific observations on education effects of these projects. One report even pinpointed education as an area for further study.

G.E. Schuh (1989), in *Human Capital and Agriculture Development in Latin America*, suggested many reasons for studying graduate students and the effects of funding graduate education. He suggested that many of the students funded for graduate school would not have chosen agriculture as a field had they not been offered scholarship. He further suggested that these students use their graduate degree to advance their own careers in the private sector, and that their education never benefited those for which it was intended—the rural poor of those countries. He cited various reasons for this. First, the students who reached graduate level in school were predominantly from urban areas and returned there after school. Second, many students who studied abroad never returned home but found employment abroad instead. Third, very few wage-earning jobs were available in the rural areas to hold the graduate students there. It is not clear whether these assertions hold for aquaculture students.

All of Schuh's ideas were purely speculative. He suggested further study be done on the effects of education of projects such as the PD/A CRSP that bring both financial and technical resources to the poor. Schuh felt that not enough evaluation of aid projects was being done to build a complete picture of their effectiveness in attaining their goals.

Methods and Materials

The objective of the current study is to profile the human capital impacts of the Global Experiment in terms of training, advancement, and the technology transfer consequences of developing-country nationals affiliated with PD/A CRSP research sites. This objective will be addressed by analysis of PD/A CRSP reports, interaction with PD/A CRSP personnel, and intensive interviews with PD/A CRSP counterparts, students, employees, and others associated with PD/A CRSP scientists. A data matrix will be defined that encompasses all sites by year of operation. A draft version of this matrix will be available for review by PD/A CRSP participants at the Annual Meeting. Data will be obtained from Program Management Office records, Annual Reports, and other available information. Based on previous research and the literature on training and capacity development associated with international research and development efforts, a series of indicators of impact will be defined that summarize the annual site data matrix. A report will be prepared that presents the data in tables and graphs portraying the relative and cumulative human capital impacts of the PD/A CRSP—overall and by its various sites.

Anticipated Benefits

Many development projects attempt to measure success in terms of crop increases, monetary figures or population data usually only quantitative in nature. The qualitative and exploratory nature of this study promises new and interesting literature. No study found to date has endeavored to reach back into a student's mind prior to schooling to trace his/her goal intentions through school to a career. Programs such as PD/A CRSP and universities alike often either neglect to trace their students after graduation or simply do not publish their findings in a meaningful manner. To trace students from prior to program entry through schooling through their careers could provide useful predictors for future testing.

For the PD/A CRSP, this study will provide evidence of knowledge dissemination. Tracing where and how knowledge travels from the students, if at all, will be valuable not only to the PD/A CRSP but also to human capital development programs in general. Once traced, the line of knowledge flow can be directed and shaped to make development programs self-perpetuating.

Acknowledgments

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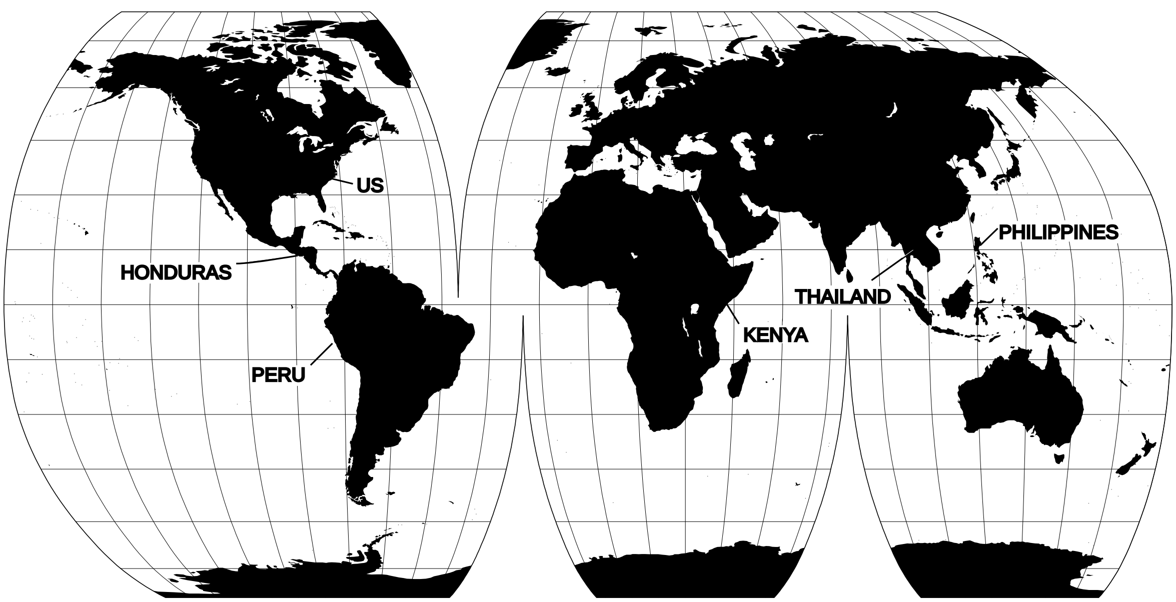
IV. Regional Research

Regional research consists of experiments, studies, and/or activities specific to PD/A CRSP research themes that are relevant to regions where the CRSP is active: Central America, South America, East Africa, and Southeast Asia. The CRSP prime site for Central America is located in Honduras; Peru is the prime site for South America; and the East Africa prime site is located in Kenya. Currently Southeast Asia has one continental prime site in Thailand; the Philippines is being considered as a second insular prime site.



PD/A CRSP Research Locations Around the World

Central America

Research efforts were conducted under the research themes of Environmental Effluents and Feeds and Fertilizers. Research into the development of estuarine models to estimate carrying capacity were delayed and will overlap with the period of the Ninth Work Plan.

A collaborative program involving PD/A CRSP researchers from Auburn University and the Laboratorio De Calidad de Agua in La Lujosa, Choluteca, Honduras, is now in its sixth year. Effluents from the shrimp culture industry in southern Honduras play a role in the water quality of the major estuaries in the region. The objective of the monitoring program is to detect positive or negative trends in water quality, to formulate and validate estuarine models that are able to predict water quality under various shrimp culture scenarios, and to estimate the carrying capacity of estuaries in relation to water quality. Water quality data collected between June 1996 and June 1997 were tabulated, and phosphorus and nitrogen concentrations were compared according to type of estuary and season. Time series graphs spanning from 1993 to 1997 were also developed for total nitrogen and total phosphorus concentrations for El Pedregal, a riverine estuary, and a number of embayment estuaries on the Gulf of Fonseca.

Results of the water quality monitoring study have indicated that the wet season is bimodal, beginning in May and ending in November, with a dry period in July. Seasonal rainfall appears to largely affect riverine estuarine water quality. During periods of heavy rainfall, the water of riverine estuaries may be almost completely replaced by freshwater as was evidenced by salinity readings of zero. During the dry season nutrients tend to concentrate but are then diluted during the wet season with rainwater discharge. If nutrient discharge is inordinately high and rainfall is delayed, the water quality of riverine estuaries may deteriorate to a level that hampers shrimp production. Producers located upstream on riverine estuaries may be even more affected by poor water quality conditions, as water exchange between the Gulf of Fonseca and the estuary decreases with distance upstream.

In comparison with riverine estuaries, CRSP researchers in Honduras found that the water quality of embayment estuaries was not as intensely affected by rainfall. Embayment estuaries have a higher assimilative capacity for nutrient discharge than riverine estuaries, and salinity fluctuations in embayment estuaries are moderated by the Gulf of Fonseca. The gulf water is also less fertile than riverine water because it is subject to a high tidal range that induces water exchange with the Pacific Ocean. This action causes a resultant dilution of nutrients. Still, spikes in nutrient concentrations may occur in small embayment estuaries during low tides. In the absence of a significant tidal exchange, nutrient concentrations are likely to develop, as water used by shrimp farms is pumped out of and discharged into the same embayment.

Research in Honduras continued to focus on the effects of dietary protein content on semi-intensive shrimp production. Previous feeding studies have suggested that feeding rates were too high for the semi-intensive production of *Penaeus vannamei* during the dry season and that wet season feeding rates might also have been too high. To further optimize shrimp production, scientists from Auburn University, the Laboratorio De Calidad de Agua, and Grupo Granjas Marinas, Choluteca, tested the effects of feed protein content and feeding rate on the semi-intensive production of *P. vannamei.* Formulated diets containing 12, 16, 20, and 30% crude protein were compared. Hatchery shrimp stocked at 250,000 post larval shrimp m^{-2} were fed six days per week at 75% of theoretical feeding curve for *P. vannamei*.

Researchers are also testing the effectiveness of CRSP-developed shrimp production systems in on-farm trials. A majority of PD/A CRSP research in southern Honduras is conducted at facilities with the necessary infrastructure available for shrimp production. Research results are then reported to shrimp farmers throughout southern Honduras, who decide whether or not they will adopt a suggested production system approach. To date a systematic effort to evaluate CRSP-developed production systems at different geographic locations has not been undertaken. To address this question, a study of four shrimp farms located on riverine and embayment estuaries in southern Honduras evaluated the growth, yield, and survival of shrimp cultured in commercially-managed ponds.

Unfortunately, the results of both of these studies were inconclusive. Unexpectedly high mortality due to Taura Syndrome resulted in high feed conversion ratios (FCRs) because of overfeeding; the computer-generated, expected mortality (75%) was exceeded in both studies by 27%, which resulted in an overestimation of feed inputs. Nevertheless, for each of the studies mentioned above, total nitrogen concentrations sampled during weekly water exchange events were not significantly different between treatments despite the increased nitrogen inputs associated with higher protein content feeds. It is important to note that the overall results obtained at the end of the experimental period for each of the experiments did reveal differences in nutrient concentrations. For the study comparing four different percentages of feed protein content, the observed mean for the discharge of nitrogen was higher for treatments receiving 20 and 30% protein feeds compared with the treatments receiving the 12 and 16% protein feeds. Furthermore, observed nutrient concentrations in discharge water for the on-farm production trials were higher than the nutrient concentrations of intake water, thus indicating a net discharge of nutrients.

Effect of Diet Protein on Semi-Intensive Production of *Penaeus vannamei* during the Rainy Season

Interim Work Plan, Honduras Study (Part Ia)

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Introduction

Shrimp culture in Honduras is practiced at the semi-intensive level, where final stocking rates vary from 5 to 11 shrimp m^{-2}, daily water exchange rates average 10% of pond volume, and formulated rations contain 20 to 40% protein. A number of studies have been conducted to determine the effect of dietary protein level and feeding rate on production of *Penaeus vannamei*. Teichert-Coddington and Rodriguez (1995) reported no significant differences in yield for *P. vannamei* in ponds stocked with 5 and 11 shrimp m^{-2} and offered a 20% or 40% protein commercial ration. A prior feed trial in Choluteca with a stocking density of 7.5 shrimp m^{-2} demonstrated that production during the dry season was not significantly affected by a 50% reduction in the feeding rate. Wet season production was significantly impacted by the 50% reduction in feeding, but feeding efficiency was improved. These results indicated that excessive feed was applied regularly during the dry season and that wet season feed rates could be reduced (although not by as much as 50%). Practical rainy season feeding rates approximated the rates indicated by the theoretical feeding curve.

Thus, it appears that shrimp yields do not improve when feed protein is increased from 20 to 40% of the ration. In fact preliminary data indicate that shrimp production during the rainy season is not affected by feed with a protein content range of 16 to 30%. The objective of this experiment was to determine the effect of dietary protein on shrimp growth and yield.

Methods and Materials

Sixteen 2-ha (± 0.08 ha SD) ponds located on a commercial shrimp farm located on a riverine estuary of the Gulf of Fonseca, Honduras were used for this randomized design study. Four diets were tested containing 12, 16, 20 or 30% crude protein (Table 1). Shrimp were fed six days per week beginning on 10 September 1996. Feed rate for each treatment was 75% of an empirically derived feeding curve for *P. vannamei*:

$$\mathrm{Log}_{10}\, y = -0.899 - 0.56\mathrm{Log}_{10}\, x$$

where y is the feed rate as a percent of biomass and x is the mean shrimp weight in grams. Feed was offered once daily. Feed rate was calculated for individual ponds and then averaged by treatment, so that all ponds within a treatment received the same quantity of feed. Feed rate was adjusted weekly, based on samples to monitor shrimp growth, taken weekly by cast net from each pond population. The weight of feed offered

Table 1. Composition of shrimp diets formulated to contain 12 to 30% crude protein.

Ingredient	Formulated Ration			
	12% Protein	*16% Protein*	*20% Protein*	*30% Protein*
Soybean Meal (48.5%)	10.0	7.7	17.8	26.1
Ground Wheat	84.4	76.5	66.2	
Fish Meal (67%)		7.5	7.5	15.0
Meat and Bone Meal		1.0	1.0	2.0
Wheat Midds				33.5
White Corn				14.0
Rice Semolina				4.5
Fish Oil		2.0	2.0	
Palm Oil	2.7			
$CaCO_3$	2.9	3.3	3.5	2.9
Bentonite		2.0	2.0	
Maxi-bond				2.0
Total	100.0	100.0	100.0	100.0

divided by the gross yield of whole shrimp was used to calculate the feed conversion ratio (FCR).

Ponds were stocked with hatchery-spawned, post-larval (PL) *P. vannamei* at 250,000 PL ha^{-1} (25 PL m^{-2}) on 15 August 1996. A survival rate of 25% was assumed, to account for Taura Syndrome effects on hatchery-produced larvae; most mortality was assumed to occur during the first month following stocking. Shrimp were harvested 110 days after stocking by completely draining ponds. The total weight of shrimp was obtained for each pond and mean individual weight was determined by weighing a sample of 300 shrimp per pond.

No water was exchanged during the first three weeks of culture. Starting with week four, water was exchanged at 20% of pond volume once weekly. In addition if the early morning dissolved oxygen concentration was ≤ 2.5 mg l^{-1}, then 5% of the pond volume was exchanged. For all water exchanges, water was discharged first and then ponds were refilled. All water exchange events were recorded. Total material exchange per pond during weekly water exchange was calculated by subtracting mass discharge from mass intake.

Water quality variables in each pond were measured upon initiation of the experiment. Beginning with week four, at the initiation of water exchange, discharge and intake water quality was monitored weekly. Intake water was sampled from supply canals, while discharge water was sampled from each pond's outfall. Initial pond water and replacement water samples were obtained with a column sampler. Water samples were analyzed for pH (measured potentiometrically), nitrate-nitrogen (measured by cadmium reduction) (Parsons et al., 1992), total ammonia-nitrogen (Parsons et al., 1992), soluble reactive phosphorus (SRP) (Grasshoff et al., 1983), chlorophyll *a* (Parsons et al., 1992), total alkalinity (measured by titration to pH 4.5 endpoint), salinity, and BOD_2 at ambient temperature. Total nitrogen and total phosphorus were determined by nitrate and phosphate analysis, respectively, after simultaneous persulfate oxidation (Grasshoff et al., 1983).

Data were analyzed by ANOVA (Haycock et al., 1992). Percent data were arcsine transformed prior to analysis. Differences were declared significant at alpha level 0.05.

Results

Shrimp survival, which was much lower than the rate anticipated to account for Taura Syndrome, averaged 5% among all treatments (Table 2); survival did not differ significantly among treatments. Feed

Table 2. Mean production (± SD) of *Penaeus vannamei* in 16 two-ha earthen ponds during a 110-day rainy season study. Post larval shrimp were stocked at 25 PL m^{-2}. Four levels of dietary protein were tested.

Variable	Formulated Ration			
	12% Protein	*16% Protein*	*20% Protein*	*30% Protein*
Gross Yield (kg ha^{-1})	186.0 ± 41.2[a]	223.0 ± 43.6[a]	277.0 ± 98.6[a]	235.0 ± 83.4[a]
Mean Weight (g $shrimp^{-1}$)	13.7 ± 1.18[a]	13.7 ± 0.77[a]	14.1 ± 1.25[a]	13.8 ± 1.38[a]
Survival (%)	5.3 ± 0.14[a]	6.6 ± 0.07[a]	7.8 ± 0.21[a]	6.3 ± 0.19[a]
FCR	6.1 ± 1.41[a]	4.9 ± 0.98[a]	4.1 ± 1.26[a]	5.0 ± 1.48[a]
Total Feed Offered (kg ha^{-1})	1088.0 ± 10.1[a]	1065.0 ± 45.3[a]	1045.0 ± 42.1[a]	1081.0 ± 37.7[a]

[a] Means with the same superscript designation are not significantly different ($P > 0.05$). Horizontal comparison only.

protein level did not significantly affect gross yield, mean shrimp weight, or FCR (Table 2), nor did it affect shrimp growth (Figure 1). Similar quantities of feed were offered in all treatments, however the total quantity of nitrogen added increased significantly with feed protein content.

Total nitrogen, total ammonia-nitrogen, total phosphorus, soluble reactive phosphorus, and chlorophyll *a* concentrations of pond intake and discharge water did not differ significantly (Table 3). Intake water had significantly greater oxidized nitrogen and significantly lower BOD_2 concentrations than discharge water (Table 3). There were no treatment differences among discharge water nutrient concentration variables (Table 3). No significant relationship was detected between total quantity of feed added per pond and concentration of any nutrient in discharge water.

The mean volume discharged from ponds per exchange event did not differ significantly among treatments; the global mean volume discharged was 2,624 m^3. Mean material exchange was negative (i.e., net discharge) for total nitrogen, total phosphorus, soluble reactive phosphorus

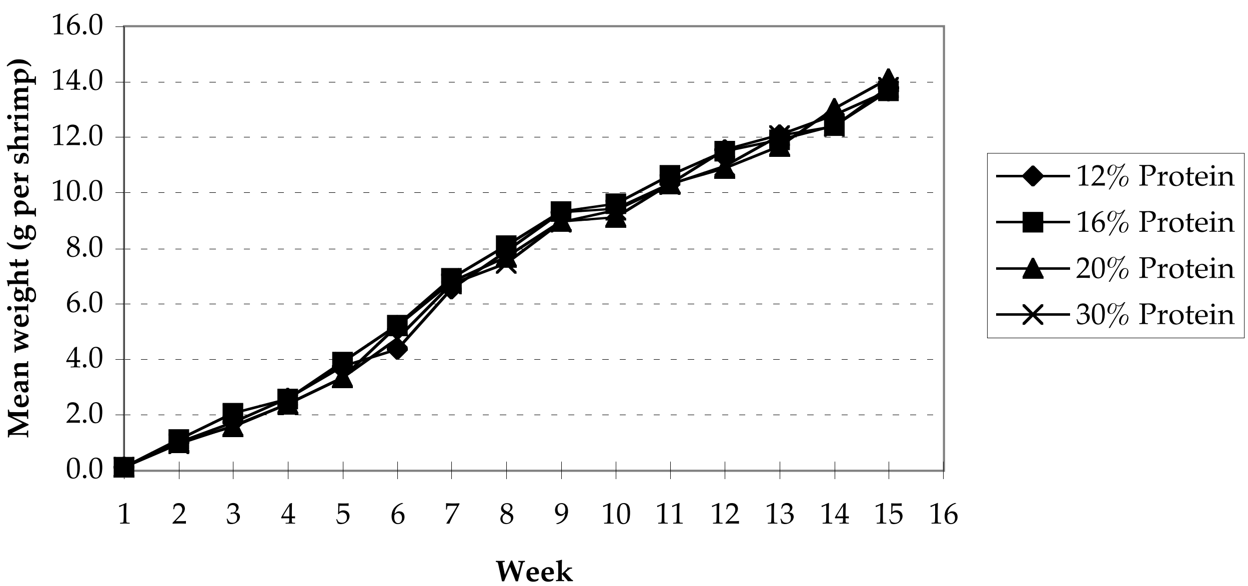

Figure 1. Growth of *Penaeus vannamei* stocked in two-ha earthen ponds at 25 post larvae m^{-2} and fed one of four dietary protein level feeds during a 110-d grow-out in Honduras.

Table 3. Mean nutrient concentrations (± SD) of intake and discharge water from 16 two-ha earthen ponds stocked with *Penaeus vannamei* (25 m^{-2}) during a rainy season study that tested four levels of dietary protein.

Variable	Intake Water	Discharge Water			
		12% Protein	*16% Protein*	*20% Protein*	*30% Protein*
Total Nitrogen (mg l^{-1})	0.78 ± 0.015^a	1.38 ± 0.463^a	1.26 ± 0.398^a	1.43 ± 0.515^a	1.66 ± 0.511^a
Total Ammonia-N (mg l^{-1} NH_3-N)	0.08 ± 0.044^a	0.06 ± 0.014^a	0.06 ± 0.025^a	0.05 ± 0.013^a	0.05 ± 0.016^a
Oxidized N (mg l^{-1} NO_2-NO_3-N)	0.042 ± 0.035^a	0.003 ± 0.001^b	0.002 ± 0.001^b	0.005 ± 0.008^b	0.006 ± 0.008^b
Total Phosphorus (mg l^{-1})	0.20 ± 0.035^a	0.24 ± 0.035^a	0.29 ± 0.023^a	0.24 ± 0.062^a	0.30 ± 0.089^a
Soluble Reactive Phosphate (mg l^{-1} PO_4-P)	0.11 ± 0.027^a	0.11 ± 0.046^a	0.15 ± 0.014^a	0.10 ± 0.065^a	0.14 ± 0.112^a
Chlorophyll *a* (mg m^{-3})	33.0 ± 3.80^a	59.5 ± 40.06^a	47.5 ± 32.77^a	67.6 ± 37.85^a	95.2 ± 50.88^a
BOD_2 (mg l^{-1})	2.9 ± 0.46^b	5.8 ± 1.78^a	5.5 ± 1.76^a	6.4 ± 2.08^a	6.8 ± 1.92^a

[a,b] Means with the same superscript designation are not significantly different ($P > 0.05$). Horizontal comparions only.

Table 4. Mean net nutrient exchange (intake minus discharge) per water exchange event (± SD) in 16 two-ha earthen ponds stocked with *Penaeus vannamei* (25 m^{-2}) during a 110-d rainy season study that tested four levels of dietary protein. Parentheses indicate negative values.

Variable	Formulated Ration			
	12% Protein	*16% Protein*	*20% Protein*	*30% Protein*
Total Nitrogen (kg)	(1.61) ± 1.110[a]	(1.25) ± 0.935[a]	(1.90) ± 1.415[a]	(2.51) ± 1.408[a]
Total Ammonia-N (g)	16.1 ± 41.87[a]	15.5 ± 59.81[a]	60.6 ± 30.03[a]	45.9 ± 37.40[a]
NO_3-NO_2-N (g)	85.2 ± 8.43[a]	82.3 ± 2.10[a]	79.2 ± 24.38[a]	73.6 ± 20.04[a]
Total Phosphorus (g)	(118) ± 79.6[a]	(229) ± 52.1[a]	(123) ± 175.9[a]	(279) ± 212.3[a]
Soluble Reactive Phosphorus (g)	(7.3) ± 118.02[a]	(113.1) ± 37.11[a]	31.6 ± 193.08[a]	(85.2) ± 287.68[a]
Chlorophyll *a* (g)	(68.9) ± 99.46[a]	(37.1) ± 78.50[a]	(99.4) ± 103.82[a]	(169.9) ± 137.67[a]
BOD_2 (kg)	(7.4) ± 4.24[a]	(6.4) ± 4.14[a]	(9.8) ± 5.72[a]	(10.8) ± 5.19[a]

[a] Means with the same superscript designation are not significantly different ($P > 0.05$).

(with the exception of the 20% protein treatment where more SRP was taken in than discharged), and chlorophyll *a*. Total amounts of ammonia-nitrogen and nitrate-nitrite-nitrogen taken into ponds were greater than amounts discharged (Table 4). There were no significant differences in material exchange among treatments.

Discussion

The unexpectedly high shrimp mortality made it impossible to determine the effect of dietary protein level on shrimp production. Effects of dietary protein content should become apparent only when the shrimp biomass has attained the critical standing crop and the biomass of natural food organisms in the pond is no longer adequate to support rapid shrimp growth. Shrimp yields in this experiment were 30 to 44% of rainy season yields reported for Taura Syndrome-affected ponds in Honduras (Teichert-Coddington et al., 1996; Teichert-Coddington et al., 1997).

The question of whether dietary protein level can be reduced below 20% for semi-intensively managed shrimp ponds in Honduras remains unanswered. Results of other research conducted in Honduras indicate that 30% protein feed did not result in increased shrimp production compared to 20% protein feed (Green et al., 1997; Teichert-Coddington et al., 1997). Shrimp yield and growth were similar when shrimp were stocked in ponds at 5 to 11 *P. vannamei* m^{-2} and offered a 20 or 40% protein formulated ration (Teichert-Coddington and Rodriguez, 1995). No significant difference in shrimp yield was reported when a 29 or 37% protein feed was offered to *P. vannamei* stocked in earthen ponds at four to eight shrimp m^{-2} (Teichert-Coddington and Arrue, 1988). *Penaeus vannamei* growth in ponds stocked with seven to nine shrimp m^{-2} did not differ significantly among the following treatments: no external inputs, cow manure, cow manure and chemical fertilizer, or 20% protein feed (Lee and Shlesser, 1984). Since it is indicated that feed protein content could be reduced to below 20% for semi-intensive *P. vannamei* culture, this study should be repeated using post larval *P. vannamei* with demonstrated and/or improved survivorship, such as wild-caught *P. vannamei*.

Feed conversion ratios were very high for this experiment because of overfeeding. The computer-generated feed curve incorporated the expected mortality (75% of stocked animals), but because mortality exceeded anticipated levels by 27%, feed inputs were overestimated. While it is impossible to make inferences regarding treatment effects on FCR, these results clearly demonstrate the difficulty in achieving efficient feed management in ponds affected by Taura Syndrome.

No treatment differences were detected in total nitrogen concentrations in pond effluents during weekly water exchange events despite nitrogen additions (in the form of feed) that increased significantly with increased feed protein level. However, the observed mean discharge of nitrogen was higher with the 20 and 30% protein feeds compared with the lower protein feeds. Previous studies have reported that weekly exchange events discharged organically-rich water—measured as total nitrogen, total phosphorus, chlorophyll *a*, and BOD_2—into estuaries (Green et al., 1997; Teichert-Coddington et al., 1996; Teichert-Coddington et al., 1997). Inorganic nitrogen and phosphorus entering ponds was also converted to organic matter that was discharged into estuaries.

Anticipated Benefits

This study was designed to determine the effect of feed protein level on growth and yield of semi-intensively cultured *P. vannamei* in Honduras, with the goal of reducing nitrogen inputs as feed to ponds. However, because shrimp survival was only 20% of that expected, it was impossible to evaluate treatment effects. This experiment should be repeated.

Acknowledgments

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Estuarine Water Quality Monitoring and Estuarine Carrying Capacity

Eighth Work Plan, Honduras Research 2 (HR2)

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Introduction

A collaborative program was begun in 1993 to monitor water quality in major estuaries supporting the shrimp culture industry in southern Honduras (Teichert-Coddington, 1995). This program combines the time and resources of commercial shrimp farming companies in Honduras, the Government of Honduras, local and international educational institutions, and the PD/A CRSP (Green et al., 1997). The monitoring program is unique in that it has generated long-term, continuous, systematic data on estuarine water quality in a shrimp producing area.

Water quality monitoring continues in most of the 13 original sites and has expanded to 29 sites. The additional monitoring sites are primarily small- to medium-size farms located on estuaries and embayments not previously sampled. Some embayments have little or no history of shrimp farming, so baseline water quality prior to the effects of shrimp farming is being established.

The objectives of the water quality monitoring are to:

1. detect changes in water quality;
2. formulate and validate models to predict future estuarine water quality conditions under various scenarios; and
3. estimate carrying capacity of estuaries based on water quality, farm chemical budgets, and estuarine fluid dynamics.

This report focuses on water quality monitoring; modeling and carrying capacity studies will be completed in the following year.

Methods and Materials

Water samples were taken every one to two weeks from the pump discharge of shrimp farms during high tide. This sample presumably represented an estuarine column sample because the pump intake, located at the bottom of the estuary, created a vortex at the water surface. Samples were put on ice and transported to the laboratory where analyses commenced within six hours of sampling. The Choluteca River was sampled at La Lujosa, which is located downstream from the city of Choluteca and upstream from tidal influence.

Water was analyzed for total settleable solids (APHA, 1985), nitrate-nitrogen (by cadmium column reduction to nitrite) (Parsons et al., 1992), total ammonia-nitrogen (Parsons et al., 1992), filterable reactive phosphate (Grasshoff et al., 1983), chlorophyll *a* (Parsons et al., 1992), total alkalinity (by titration to 4.5 pH endpoint), salinity, and BOD_2. Total nitrogen and total phosphorus were determined by nitrate and phosphate analysis, respectively, after simultaneous persulfate oxidation in a strong base (Grasshoff et al., 1983).

Data collected from June 1996 to June 1997 were tabulated by sampling site. For some of the new sites only limited data is available and these sites

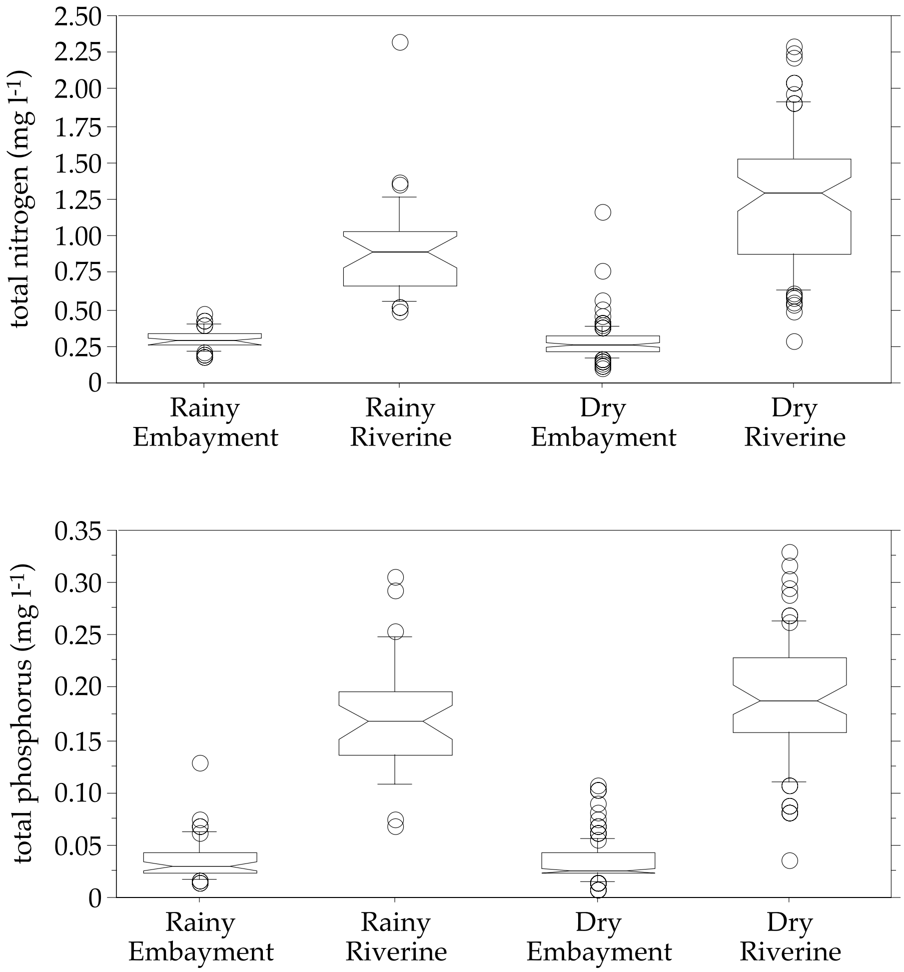


Figure 1. Box plots show comparison of total nitrogen and total phosphorus concentration median values from embayments and a riverine estuary, El Pedregal, from June 1996 to June 1997. Data collected from August through the middle of November (the period of heaviest rainfall) were classified as rainy and all other data were classified as dry. The notches around the median represent 95% confidence limits.

were not included in the results. Comparisons of phosphorus and nitrogen concentrations by inlet type (embayment or riverine) and season were made with box plots. Time-series graphs were made using total nitrogen and total phosphorus concentration data from El Pedregal, a riverine estuary, and data from embayment estuaries sampled from 1993 to 1997.

Results

Data for each site are summarized in Table 1. These results were similar to those reported by Teichert-Coddington (1995). Seasonal rainfall largely determines river estuary water quality. The pattern of rainfall during the wet season is typically bimodal, beginning in May and ending in November with a dry spell during July. Nutrients, particularly nitrogen, concentrate during the dry season when freshwater input is minimal and are diluted with rainwater discharge during the wet season (Figure 1). Water in riverine estuaries is often completely displaced by fresh water during periods of heavy rainfall, as illustrated by the predominance of zero salinities measured in riverine estuaries (Table 1). Embayment water quality varied less with season and was considerably less enriched than riverine estuaries (Figure 1). No trends for long-term nitrogen or phosphorus enrichment were demonstrated in El Pedregal Estuary or embayments during the period of 1993 to 1997 (Figures 2 and 3). Results were similar for the other riverine estuaries.

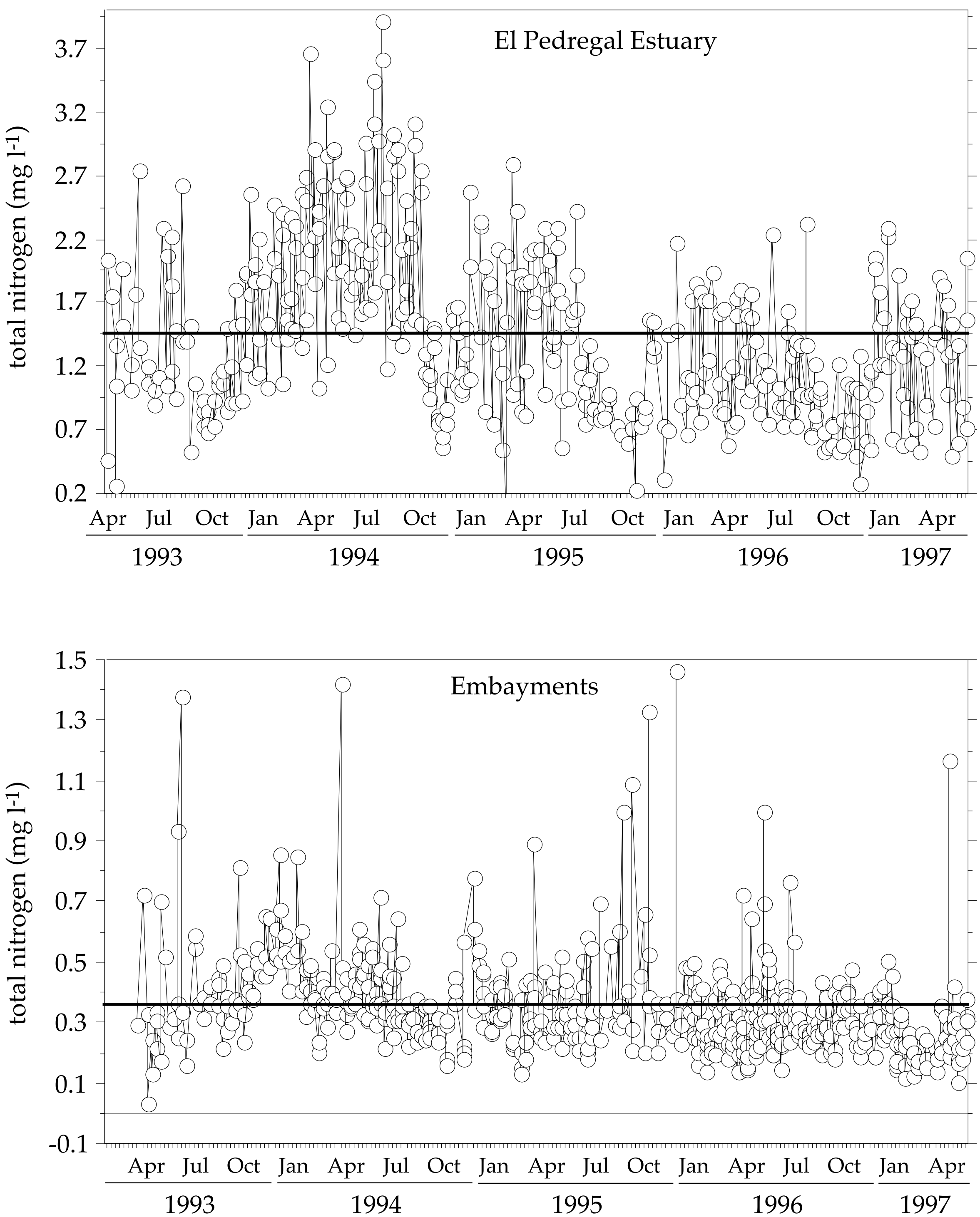
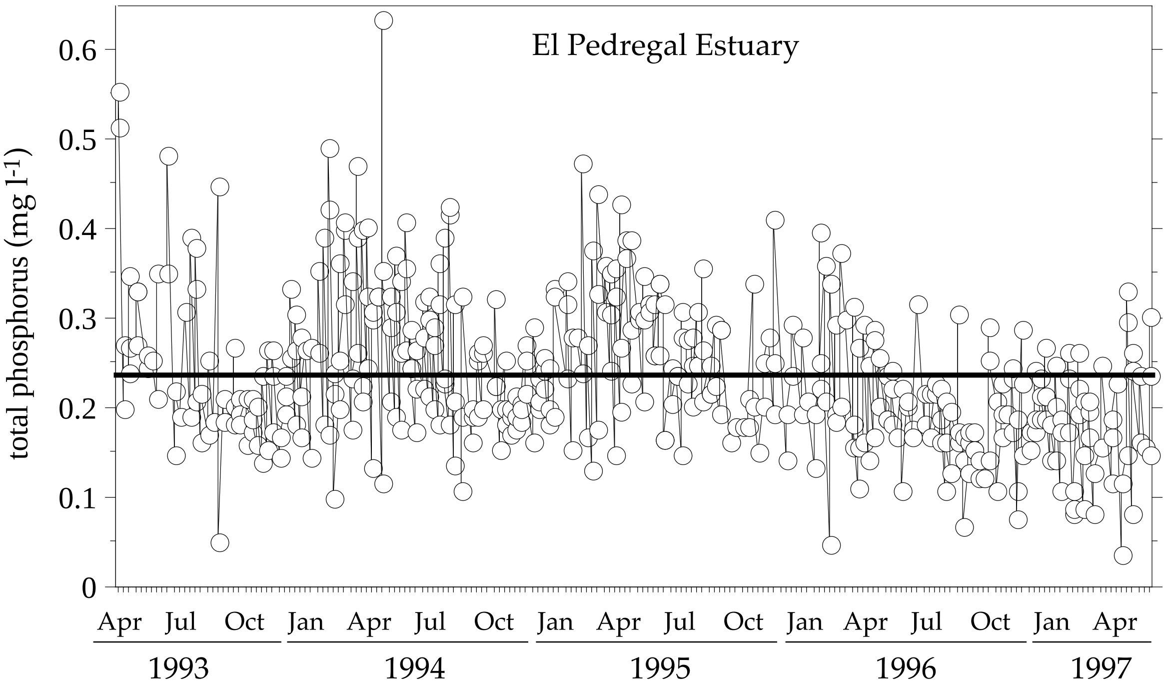


Figure 2. Total nitrogen concentrations are shown from El Pedregal Estuary and embayments of the Gulf of Fonseca from 1993 to 1997. The horizontal line in each graph is the grand mean concentration during this period.



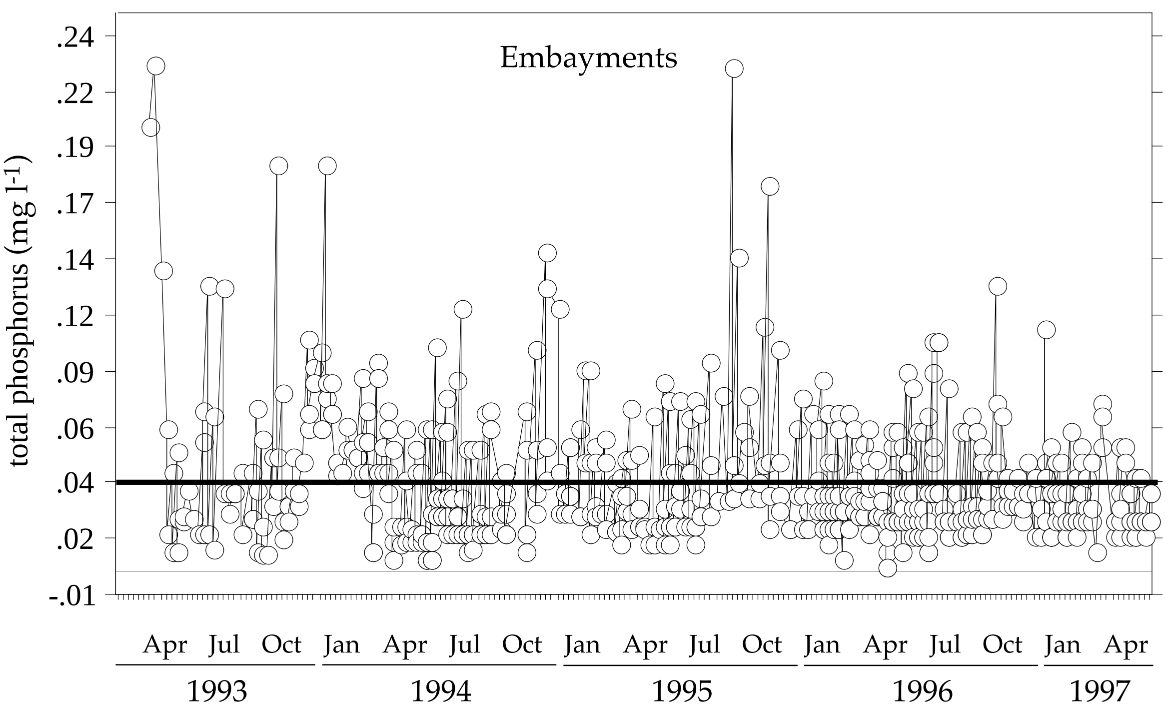


Figure 3. Total phosphorus concentrations are shown from El Pedregal Estuary and embayments of the Gulf of Fonseca from 1993 to 1997. The horizontal line in each graph is the grand mean concentration during this period.

Table 1. Summary of inlet water quality determinations from shrimp farm sites in southern Honduras from June 1996 to June 1997. Sites are labeled "riverine" or "embayment" depending on whether or not a river discharges directly into the estuary.

Variable	Mean	SD	Count	Minimum	Maximum	Median
GMSB 2 - RIVERINE						
Salinity (ppt)	18.3	13.1	32	0	37	18.8
Total Ammonia (mg l^{-1})	0.514	2.508	33	0.002	14.475	0.053
Total Nitrogen (mg l^{-1})	0.815	0.209	32	0.455	1.531	0.798
Nitrates + Nitrites (mg l^{-1})	0.333	0.177	32	0.067	0.807	0.36
Total Phosphorus (mg l^{-1})	0.166	0.041	32	0.076	0.277	0.16
React. Filter. Phosphate (mg l^{-1})	0.129	0.025	33	0.067	0.184	0.129
Total Alkalinity (mg l^{-1})	125.4	28.6	31	65.7	160.3	135.6
Chlorophyll *a* (mg l^{-1})	9.6	5.5	32	0	21.2	9.35
BOD_2 (mg l^{-1})	1.4	1.0	32	0.5	5.25	1.25
Settleable Solids (mg l^{-1})	0.2	0.5	32	0	2.3	0.05
GMSB 1 - RIVERINE						
Salinity (ppt)	17.9	11.7	31	0	33.5	19.0
Total Ammonia (mg l^{-1})	0.088	0.06	32	0.002	0.202	0.099
Total Nitrogen (mg l^{-1})	0.85	0.281	31	0.5	1.591	0.822
Nitrates + Nitrites (mg l^{-1})	0.299	0.149	32	0.008	0.566	0.318
Total Phosphorus (mg l^{-1})	0.147	0.047	31	0.036	0.289	0.15
React. Filter. Phosphate (mg l^{-1})	0.108	0.028	32	0.029	0.151	0.108
Total Alkalinity (mg l^{-1})	117.4	31.2	29	51	156.4	125.9
Chlorophyll *a* (mg l^{-1})	16.9	10.0	31	4.1	48.3	14.7
BOD_2 (mg l^{-1})	1.5	0.6	31	0.2	2.75	1.5
Settleable Solids (mg l^{-1})	1.4	1.8	31	0	8	0.5
SEA FARMS 1 - EMBAYMENT						
Salinity (ppt)	30.0	4.0	20	16.5	35.5	30.8
Total Ammonia (mg l^{-1})	0.036	0.04	21	0.003	0.131	0.016
Total Nitrogen (mg l^{-1})	0.272	0.087	21	0.15	0.436	0.263
Nitrates + Nitrites (mg l^{-1})	0.007	0.008	21	0	0.033	0.005
Total Phosphorus (mg l^{-1})	0.055	0.02	21	0.036	0.129	0.05
React. Filter. Phosphate (mg l^{-1})	0.033	0.023	21	0.003	0.104	0.025
Total Alkalinity (mg l^{-1})	114.9	8.5	19	97.3	127.7	115.4
Chlorophyll *a* (mg l^{-1})	4.4	3.7	20	0	15.9	4.25
BOD_2 (mg l^{-1})	1.2	0.6	21	0.4	3.45	1.15
Settleable Solids (mg l^{-1})	0	0	20	0	0	0

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
SEA FARMS 2 - EMBAYMENT						
Salinity (ppt)	29.4	3.0	20	23	35.5	30.0
Total Ammonia (mg l^{-1})	0.034	0.035	21	0.001	0.132	0.03
Total Nitrogen (mg l^{-1})	0.278	0.062	21	0.163	0.355	0.299
Nitrates + Nitrites (mg l^{-1})	0.015	0.025	21	0	0.117	0.007
Total Phosphorus (mg l^{-1})	0.03	0.019	21	0.016	0.109	0.023
React. Filter. Phosphate (mg l^{-1})	0.009	0.009	21	0	0.039	0.01
Total Alkalinity (mg l^{-1})	110.3	8.3	20	92.6	120.8	113.7
Chlorophyll *a* (mg l^{-1})	3.3	1.7	20	0	6.6	2.9
BOD_2 (mg l^{-1})	1.5	1.1	21	0.65	5	1.1
Settleable Solids (mg l^{-1})	0	0	20	0	0	0
LA JAGUA - RIVERINE						
Salinity (ppt)	14.1	12.9	30	0	34	12.3
Total Ammonia (mg l^{-1})	0.084	0.06	31	0.001	0.24	0.084
Total Nitrogen (mg l^{-1})	0.952	0.237	30	0.578	1.493	0.901
Nitrates + Nitrites (mg l^{-1})	0.417	0.182	31	0.055	0.907	0.382
Total Phosphorus (mg l^{-1})	0.176	0.037	29	0.11	0.254	0.175
React. Filter. Phosphate (mg l^{-1})	0.128	0.028	30	0.079	0.219	0.127
Total Alkalinity (mg l^{-1})	123.7	38.7	29	49	171.7	146.7
Chlorophyll *a* (mg l^{-1})	20.7	13.9	31	2.4	61.6	17.7
BOD_2 (mg l^{-1})	2.5	1.5	30	0.85	7.5	2.075
Settleable Solids (mg l^{-1})	2.2	3.3	29	0.05	14	0.8
CRIMASA - RIVERINE						
Salinity (ppt)	23.2	15.0	23	1.5	47	29.0
Total Ammonia (mg l^{-1})	0.114	0.109	24	0	0.383	0.092
Total Nitrogen (mg l^{-1})	0.931	0.191	23	0.586	1.233	0.971
Nitrates + Nitrites (mg l^{-1})	0.26	0.198	24	0.005	0.641	0.207
Total Phosphorus (mg l^{-1})	0.187	0.051	23	0.116	0.29	0.175
React. Filter. Phosphate (mg l^{-1})	0.152	0.056	24	0.024	0.233	0.167
Total Alkalinity (mg l^{-1})	131.4	34.9	22	57.9	174.6	150.25
Chlorophyll *a* (mg l^{-1})	11.9	11.3	24	0	45.9	8.6
BOD_2 (mg l^{-1})	2.0	1.1	23	0.45	5.7	1.6
Settleable Solids (mg l^{-1})	0.8	1.0	22	0	3.5	0.4

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
CONCHAL - EMBAYMENT						
Salinity (ppt)	28.8	3.7	31	21	34	29.0
Total Ammonia (mg l^{-1})	0.024	0.02	33	0	0.088	0.018
Total Nitrogen (mg l^{-1})	0.259	0.07	32	0.119	0.458	0.258
Nitrates + Nitrites (mg l^{-1})	0.01	0.009	33	0	0.036	0.008
Total Phosphorus (mg l^{-1})	0.035	0.013	31	0.016	0.07	0.03
React. Filter. Phosphate (mg l^{-1})	0.01	0.005	33	0	0.022	0.01
Total Alkalinity (mg l^{-1})	109.6	9.0	31	93.1	126.9	112.6
Chlorophyll *a* (mg l^{-1})	3.9	2.5	33	0	9.7	2.9
BOD_2 (mg l^{-1})	1.1	1.3	32	0.15	7.65	0.85
Settleable Solids (mg l^{-1})	0.01	0.02	30	0	0.05	0
CULCAMAR 2 - EMBAYMENT						
Salinity (ppt)	17.3	9.5	12	1	27	20.3
Total Ammonia (mg l^{-1})	0.109	0.111	13	0.005	0.36	0.066
Total Nitrogen (mg l^{-1})	0.497	0.135	12	0.257	0.676	0.499
Nitrates + Nitrites (mg l^{-1})	0.013	0.009	13	0	0.027	0.012
Total Phosphorus (mg l^{-1})	0.104	0.148	13	0.023	0.537	0.036
React. Filter. Phosphate (mg l^{-1})	0.094	0.165	13	0	0.478	0.011
Total Alkalinity (mg l^{-1})	105.5	19.7	12	64.7	132.7	101.6
Chlorophyll *a* (mg l^{-1})	9.8	6.7	13	4.3	29.4	7.2
BOD_2 (mg l^{-1})	1.1	0.8	12	0.3	2.6	0.75
Settleable Solids (mg l^{-1})	0.1	0.2	13	0	0.5	0.05
CADELPA LAS ARENAS - EMBAYMENT						
Salinity (ppt)	26.6	6.8	30	9	34	28.8
Total Ammonia (mg l^{-1})	0.029	0.033	31	0	0.176	0.023
Total Nitrogen (mg l^{-1})	0.289	0.099	30	0.106	0.504	0.284
Nitrates + Nitrites (mg l^{-1})	0.023	0.028	31	0	0.101	0.01
Total Phosphorus (mg l^{-1})	0.026	0.014	30	0.009	0.076	0.023
React. Filter. Phosphate (mg l^{-1})	0.006	0.008	30	0	0.035	0.003
Total Alkalinity (mg l^{-1})	104.6	14.9	29	58.9	122.8	107.6
Chlorophyll *a* (mg l^{-1})	3.5	1.7	31	0	7.5	2.9
BOD_2 (mg l^{-1})	0.8	0.4	30	0.1	2.25	0.8
Settleable Solids (mg l^{-1})	0.003	0.018	30	0	0.1	0

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
CADELPA-TULITO 1 - RIVERINE						
Salinity (ppt)	13.6	13.6	32	0	39	6.3
Total Ammonia (mg l^{-1})	0.206	0.144	33	0.027	0.495	0.177
Total Nitrogen (mg l^{-1})	1.311	0.472	32	0.532	2.325	1.306
Nitrates + Nitrites (mg l^{-1})	0.225	0.226	33	0.002	0.784	0.098
Total Phosphorus (mg l^{-1})	0.21	0.054	32	0.089	0.307	0.218
React. Filter. Phosphate (mg l^{-1})	0.151	0.073	33	0	0.287	0.177
Total Alkalinity (mg l^{-1})	131.6	44.4	31	58.9	182.2	150.5
Chlorophyll *a* (mg l^{-1})	32.0	25.0	33	8.1	119.6	24.9
BOD_2 (mg l^{-1})	3.5	1.7	32	1.15	8.7	3.35
Settleable Solids (mg l^{-1})	0.6	0.7	31	0	3.5	0.3
CADEMA - EMBAYMENT						
Salinity (ppt)	27.5	5.3	33	15.5	34	29.5
Total Ammonia (mg l^{-1})	0.027	0.021	35	0	0.095	0.025
Total Nitrogen (mg l^{-1})	0.296	0.172	34	0.123	1.17	0.266
Nitrates + Nitrites (mg l^{-1})	0.024	0.027	35	0	0.12	0.012
Total Phosphorus (mg l^{-1})	0.03	0.013	34	0.016	0.076	0.024
React. Filter. Phosphate (mg l^{-1})	0.01	0.007	35	0	0.029	0.01
Total Alkalinity (mg l^{-1})	108.1	11.5	33	82.3	123.8	111.9
Chlorophyll *a* (mg l^{-1})	3.4	2.1	35	0	10	2.7
BOD_2 (mg l^{-1})	0.9	0.8	33	0.15	5.05	0.85
Settleable Solids (mg l^{-1})	0.05	0.14	34	0	0.7	0
BIOMAR - RIVERINE						
Salinity (ppt)	19.8	11.9	28	0.5	34.5	21.3
Total Ammonia (mg l^{-1})	0.063	0.061	29	0.001	0.199	0.032
Total Nitrogen (mg l^{-1})	0.61	0.192	29	0.267	1.129	0.644
Nitrates + Nitrites (mg l^{-1})	0.212	0.126	29	0.002	0.407	0.22
Total Phosphorus (mg l^{-1}))	0.137	0.064	29	0.063	0.379	0.116
React. Filter. Phosphate (mg l^{-1})	0.089	0.032	29	0.001	0.163	0.087
Total Alkalinity (mg l^{-1})	111.0	30.7	27	29.9	150.5	122.8
Chlorophyll *a* (mg l^{-1})	9.0	4.1	29	2.7	17.8	8.4
BOD_2 (mg l^{-1})	1.1	0.5	28	0.15	2.5	1.125
Settleable Solids (mg l^{-1})	0.25	0.27	28	0	1	0.1

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
AQUACULTIVOS #2 - RIVERINE						
Salinity (ppt)	3.0	5.8	23	0	20.5	0.5
Total Ammonia (mg l^{-1})	0.069	0.086	24	0.011	0.301	0.035
Total Nitrogen (mg l^{-1})	0.585	0.259	24	0.237	1.264	0.526
Nitrates + Nitrites (mg l^{-1})	0.064	0.136	24	0	0.505	0.003
Total Phosphorus (mg l^{-1})	0.227	0.1	24	0.109	0.411	0.216
React. Filter. Phosphate (mg l^{-1})	0.19	0.074	24	0.039	0.317	0.208
Total Alkalinity (mg l^{-1})	155.3	34.7	23	88.2	217.5	161.9
Chlorophyll *a* (mg l^{-1})	27.0	31.9	24	4	165.4	19.05
BOD_2 (mg l^{-1})	2.7	1.4	24	0.05	5.1	2.85
Settleable Solids (mg l^{-1})	0.28	0.56	23	0	2.8	0.1
AQUACULTIVOS - RIVERINE						
Salinity (ppt)	14.1	13.2	34	0	34	12.0
Total Ammonia (mg l^{-1})	0.122	0.08	35	0.001	0.395	0.111
Total Nitrogen (mg l^{-1})	1.011	0.31	35	0.316	1.841	0.976
Nitrates + Nitrites (mg l^{-1})	0.353	0.149	35	0.033	0.782	0.345
Total Phosphorus (mg l^{-1})	0.169	0.053	35	0.09	0.363	0.163
React. Filter. Phosphate (mg l^{-1})	0.124	0.043	35	0.052	0.261	0.115
Total Alkalinity (mg l^{-1})	119.3	36.3	32	50.2	197	132.1
Chlorophyll *a* (mg l^{-1})	17.7	12.6	35	2.4	61.4	15.9
BOD_2 (mg l-1)	2.4	1.5	35	0.8	7.95	2.15
Settleable Solids (mg l^{-1})	1.9	3.2	34	0.05	16	0.7
AQUACULTURA FONSECA - RIVERINE						
Salinity (ppt)	11.8	12.1	27	0.5	37.5	5.0
Total Ammonia (mg l^{-1})	0.239	0.124	28	0.006	0.511	0.221
Total Nitrogen (mg l^{-1})	1.291	0.497	28	0.292	2.293	1.319
Nitrates + Nitrites (mg l^{-1})	0.307	0.243	28	0.015	0.787	0.253
Total Phosphorus (mg l^{-1})	0.19	0.062	28	0.07	0.331	0.19
React. Filter. Phosphate (mg l^{-1})	0.144	0.057	28	0.042	0.254	0.13
Total Alkalinity (mg l^{-1})	123.6	47.8	27	39.2	181.3	138.6
Chlorophyll *a* (mg l^{-1})	26.7	14.6	28	4.5	61.1	23.85
BOD_2 (mg l^{-1})	2.7	1.2	28	1	5	2.45
Settleable Solids (mg l^{-1})	1.6	2.6	27	0	12.8	0.6

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
EL FARO - RIVERINE						
Salinity (ppt)	15.5	15.9	29	0	49	6.5
Total Ammonia (mg l^{-1})	0.2	0.135	30	0.016	0.6	0.196
Total Nitrogen (mg l^{-1})	1.042	0.357	29	0.25	1.974	1.056
Nitrates + Nitrites (mg l^{-1})	0.254	0.223	30	0	0.791	0.222
Total Phosphorus (mg l^{-1})	0.235	0.089	29	0.103	0.484	0.249
React. Filter. Phosphate (mg l^{-1})	0.198	0.075	30	0.076	0.424	0.205
Total Alkalinity (mg l^{-1})	140.8	49.0	27	43.1	223.2	163.8
Chlorophyll *a* (mg l^{-1})	11.4	12.0	30	0	55.5	7.65
BOD_2 (mg l^{-1})	2.1	1.2	28	0.8	6.3	2
Settleable Solids (mg l^{-1})	3.0	7.4	29	0	31	0.1
FINCASUR - RIVERINE						
Salinity (ppt)	2.0	2.2	12	0	6.5	1.5
Total Ammonia (mg l^{-1})	0.118	0.087	12	0.032	0.35	0.104
Total Nitrogen (mg l^{-1})	0.847	0.318	12	0.43	1.346	0.804
Nitrates + Nitrites (mg l^{-1})	0.091	0.138	12	0.003	0.373	0.019
Total Phosphorus (mg l^{-1})	0.216	0.072	12	0.103	0.379	0.199
React. Filter. Phosphate (mg l^{-1})	0.147	0.059	12	0.046	0.287	0.138
Total Alkalinity (mg l^{-1})	98.9	26.1	11	51.9	129.4	95.5
Chlorophyll *a* (mg l^{-1})	30.8	27.1	12	6	81.9	21.35
BOD_2 (mg l^{-1})	3.7	2.2	12	1.25	8.7	3.25
Settleable Solids (mg l^{-1})	2.3	6.3	12	0.05	22	0.25
ICASUR - RIVERINE						
Salinity (ppt)	16.8	12.8	16	0	32.5	18.3
Total Ammonia (mg l^{-1})	0.093	0.064	16	0.002	0.18	0.074
Total Nitrogen (mg l^{-1})	0.469	0.274	15	0.208	1.289	0.422
Nitrates + Nitrites (mg l^{-1})	0.075	0.06	16	0	0.189	0.07
Total Phosphorus (mg l^{-1})	0.082	0.04	15	0.036	0.182	0.076
React. Filter. Phosphate (mg l^{-1})	0.042	0.022	16	0.017	0.097	0.039
Total Alkalinity (mg l^{-1})	116.8	37.9	15	41.5	170.8	124.5
Chlorophyll *a* (mg l^{-1})	5.3	3.3	16	0	13.1	4.6
BOD_2 (mg l^{-1})	1.7	2.2	14	0.15	8.95	1
Settleable Solids (mg l^{-1})	0	0	3	0	0	0

Table 1. Continued.

Variable	Mean	SD	Count	Minimum	Maximum	Median
CHOLUTECA RIVER AT LA LUJOSA						
Salinity (ppt)	0	0	36	0	0	0
Total Ammonia (mg l^{-1})	0.044	0.069	37	0	0.401	0.025
Total Nitrogen (mg l^{-1})	0.726	0.368	36	0.311	2.534	0.704
Nitrates + Nitrites (mg l^{-1})	0.242	0.297	37	0	1.35	0.137
Total Phosphorus (mg l^{-1})	0.251	0.125	36	0.103	0.598	0.229
React. Filter. Phosphate (mg l^{-1})	0.194	0.093	37	0.015	0.365	0.184
Total Alkalinity (mg l^{-1})	119.1	38.0	35	49	166	137.6
Chlorophyll *a* (mg l^{-1})	25.5	20.8	36	1.9	77.9	23.9
BOD_2 (mg l^{-1})	2.4	1.6	35	0.3	8.25	2.2
Settleable Solids (mg l^{-1})	0.23	0.41	36	0	1.8	0.05

Discussion

Cyclical trends for short-term enrichment in riverine estuaries are related to season. Regular rains flush estuaries and reduce the danger of long-term eutrophication. However, the particularly high concentrations of nitrogen and phosphorus observed during the summer of 1994 illustrate that short-term nutrient enrichment can reach possibly dangerous levels. Tardy rains and inordinately high nutrient discharge from shrimp farms could result in water quality conditions that are not conducive to shrimp growth. Producers located upstream in the estuaries are particularly vulnerable to poor water quality, because estuarine exchange with the gulf decreases rapidly with distance upstream (Teichert-Coddington, 1995).

Shrimp growth is coincidentally slow during the summers, probably because of cooler temperatures (Teichert-Coddington et al., 1994), and feeding should be reduced accordingly. Some smaller farms close during the summer months because of slow shrimp growth. Dry season water quality is currently manageable in most riverine estuaries, but increased expansion of farms or increased stocking densities on existing farms could cause eutrophication of these estuaries.

Embayment water quality is much more stable during the year because it is not as drastically affected by rainfall and has a higher capacity for assimilation of discharged nutrients. Salinities fall during the wet season with increased river discharge, but the fluctuations are moderated by the larger body of gulf water. A high tidal range (1.5 to 3.5 m) which promotes water exchange and nutrient dilution with the Pacific Ocean affects the Gulf of Fonseca—gulf water is less fertile than riverine water. Spikes in nutrient concentration occur in small embayments probably during periods of low tides. Nutrients may remain concentrated until a good tidal exchange replaces the embayment water.

Anticipated Benefits

The estuarine water quality database serves to track long-term changes in water quality in estuaries of the shrimp-producing region of southern Honduras. These data will be used in the development of carrying capacity models for the individual estuaries. Carrying capacity models will provide quantitative information to decision makers in the Government of Honduras and in the Honduran Association of Aquaculturists to allow them to formulate strategies and regulations regarding future shrimp industry development.

Acknowledgments

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On-farm Shrimp (*Penaeus vannamei*) Production Trials during the Rainy Season

Honduras Special Topics Research

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Introduction

The majority of Honduras PD/A CRSP shrimp production research is conducted on one farm because of infrastructure availability. Production systems developed through this research are then reported to shrimp farmers throughout southern Honduras. These farmers decide individually whether or not to adopt a particular system. There has not been a systematic effort to evaluate variability of developed production systems in relation to geographic variation in southern Honduras. Teichert-Coddington et al. (1996) evaluated the effect of stocking rate on shrimp yield, mean weight, and survival on three different farms during the rainy and dry seasons.

The objective of this study was to evaluate shrimp growth, yield, and survival in ponds all managed similarly on four different commercial farms in southern Honduras.

Methods and Materials

Sixteen randomly selected, earthen ponds ranging in size from 0.3 to 2.3 ha and located on four commercial shrimp farms (four ponds per farm) were used for this study. Farms were located on riverine estuaries or on an embayment of the Gulf of Fonseca, Honduras. Farms B and C were located on the same riverine estuary, while farm A was located on a different riverine estuary. Farm D was located on an embayment of the Gulf of Fonseca. Ponds were stocked with hatchery-spawned, post-larval (PL) *P. vannamei*, from the same production run at 250,000 PL ha^{-1} (25 PL m^{-2}) on 15 August 1996. A survival rate of 25% was assumed because of Taura Syndrome effects on hatchery-produced larvae. Most of the mortality was assumed to occur during the first month following stocking. Shrimp were harvested 110 days after stocking by completely draining ponds. Total weight of shrimp was recorded for each pond. Mean individual weight was determined by weighing a sample of 300 shrimp per pond.

Shrimp were fed a 30% protein commercial ration (Table 1) six days per week beginning on 10 September 1996. Feed rate for each treatment was 75% of a theoretical feeding curve for *P. vannamei*:

$$\mathrm{Log}_{10}\, y = -0.899 - 0.56\mathrm{Log}_{10}\, x$$

where y is the feed rate as a percent of biomass and x is the mean shrimp weight in grams.

Feed was offered once daily. Feed rate was calculated for individual ponds and then averaged by treatment, so that all ponds within a treatment received the same quantity of feed on a daily basis. Shrimp growth was monitored weekly by cast net samples of each pond's population. Feed rate was adjusted weekly based on shrimp samples. Feed conversion ratio (FCR) was calculated as the weight of feed offered divided by the gross yield of whole shrimp.

Table 1. Composition of shrimp diet formulated to contain 30% crude protein.

Ingredient	Formulated Ration (30% Protein)
Soybean Meal (48.5% Protein)	26.1
Fish Meal (67% Protein)	15.0
Meat and Bone Meal	2.0
Wheat Midds	33.5
White Corn	14.0
Rice Semolina	4.5
$CaCO_3$	2.9
Maxi-bond	2.0
Total	100.0

No water was exchanged during the first three weeks of culture. Water was exchanged at 20% of pond volume once weekly starting week 4. In addition, if early morning dissolved oxygen concentration was ≤ 2.5 mg l^{-1}, then 5% of the pond volume was exchanged. In all water exchanges, water was first discharged and then replacement water was added to refill ponds.

Water quality variables in each pond were measured upon initiation of the experiment and monitored weekly in discharge and intake water beginning with week four, the initiation of scheduled water exchange. Intake water was sampled from supply canals, while discharge water was sampled from each pond's outfall. Initial pond water and replacement water samples were obtained with a column sampler. Water samples were analyzed for pH (measured potentiometrically), nitrate-nitrogen (measured by cadmium reduction) (Parsons et al., 1992), total ammonia-nitrogen (Parsons et al., 1992), soluble reactive phosphorus (SRP) (Grasshoff et al., 1983), chlorophyll *a* (Parsons et al., 1992), total alkalinity (measured by titration to pH 4.5 endpoint), salinity, and BOD_2 at ambient temperature. Total nitrogen and total phosphorus were determined by nitrate and phosphate analysis, respectively, after simultaneous persulfate oxidation (Grasshoff et al., 1983).

Data were analyzed by ANOVA and regression analysis (Haycock et al., 1992). Percent data were arcsine transformed prior to analysis. Differences were declared significant at alpha level 0.05.

Results

Taura Syndrome had a greater than expected impact on shrimp survival during this study: global survival averaged 5%; however, shrimp survival differed significantly among farms. The greatest survival was observed on the farm located on the embayment of the Gulf of Fonseca (Table 2). Coefficients of variation for shrimp survival were 17.1%, 2.0%, 40.4%, and 16.0% for farms A through D, respectively. Production data from one pond on farm B was excluded from analyses because they were classified as outliers. Gross shrimp yields were low and ranged from 120 to 325 kg ha^{-1} (Table 2). Coefficients of variation for gross yield were 35.5%, 9.2%, 96.3%, and 31.4% for farms A through D, respectively. Shrimp yield increased significantly with increased survival ($r^2 = 0.885$, $P < 0.001$), while average individual weight decreased significantly with increased survival ($r^2 = 0.263$, $P < 0.05$). Shrimp growth is shown in Figure 1. Coefficients of variation for individual weight were 10.0%, 6.7%, 2.6%, and 10.8% for farms A through D, respectively. No significant differences in FCR were detected among farms (Table 2). Total feed usage (kg ha^{-1}) varied significantly among farms (Table 2). Total quantity of nitrogen added to ponds as feed increased significantly with total feed usage.

Table 2. Mean production (± SD) of *Penaeus vannamei* in 0.3- to 2.3-ha earthen ponds on four different farms during 110-day rainy season study. Post-larval shrimp were stocked at 25 PL m^{-2}. Shrimp were offered a 30% protein commercial ration.

Variable	Farm			
	A	*B*	*C*	*D*
Gross yield (kg ha^{-1})	235 ± 83.4	120 ± 11.0	127 ± 122.4	325 ± 101.6
Mean weight (g $shrimp^{-1}$)	13.8 ± 1.38	13.0 ± 0.87	17.2 ± 0.45	13.0 ± 1.40
Survival (%)	6.3 ± 0.19^{b}	2.9 ± 0.00^{c}	1.8 ± 0.30^{c}	8.9 ± 0.24^{a}
FCR	5.0 ± 1.48^{a}	6.2 ± 0.69^{a}	12.4 ± 7.6^{a}	4.1 ± 1.07^{a}
Total feed offered (kg ha^{-1})	1081 ± 37.7^{b}	738 ± 10.1^{c}	953 ± 4.7^{d}	1262 ± 11.1^{a}

[abcd] Means with the same superscript designation are not significantly different ($P > 0.05$). Horizontal comparisons only.

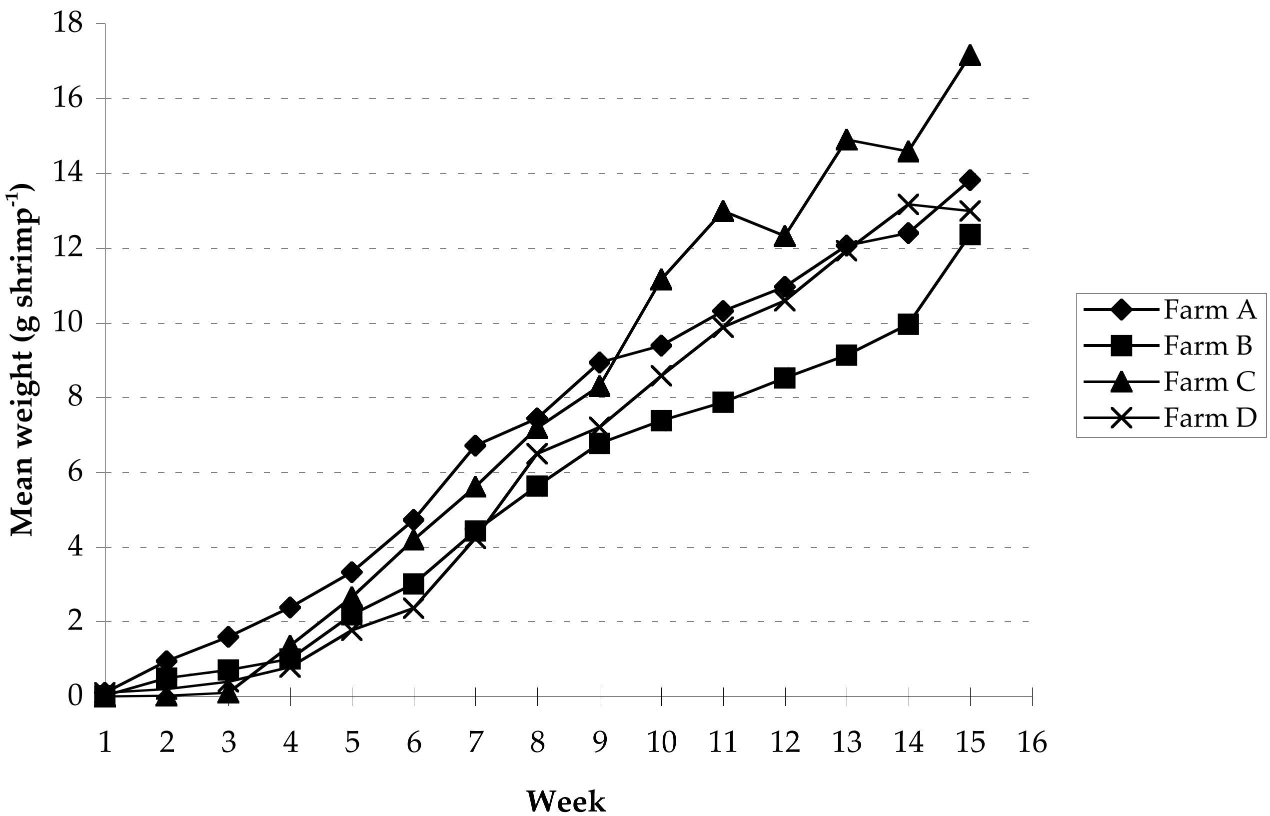

Figure 1. Growth of *Penaeus vannamei* stocked in 0.3- to 2.3-ha earthen ponds at 25 PL shrimp m^{-2} on four different commercial farms during a 110-d grow-out in Honduras. Shrimp were offered a 30% protein ration.

Table 3. Mean (± SD) nutrient concentrations of intake and discharge water in 0.3- to 2.3-ha earthen ponds stocked with *Penaeus vannamei* (25 shrimp m^{-2}) during a rainy season study implemented on four different farms. Three farms were located on two different riverine estuaries, and the fourth farm was located on an embayment of the Gulf of Fonseca, Honduras. Shrimp were offered a 30% protein commercial ration.

Variable	**Farm A[1]**		**Farm B[2]**	
	Intake	*Discharge*	*Intake*	*Discharge*
Total Nitrogen (mg l^{-1})	0.78 ± 0.015^{a}	1.66 ± 0.511^{a*}	0.73 ± 0.000^{a}	1.12 ± 0.296^{a§}
Total Ammonia-N (mg l^{-1} NH_3-N)	0.08 ± 0.044 ^{a}	0.05 ± 0.016^{a*}	0.06 ± 0.000^{a}	0.06 ± 0.038^{a*}
Oxidized N (mg l^{-1} NO_2-NO_3-N)	0.042 ± 0.035^{a}	0.006 ± 0.008^{a*}	0.100 ± 0.000^{a}	0.014 ± 0.017^{b*}
Total phosphorus (mg l^{-1})	0.20 ± 0.035^{a}	0.30 ± 0.089^{a*}	0.23 ± 0.000^{a}	0.17 ± 0.043^{a§}
Sol. reactive phosphate (mg l^{-1} PO_4-P)	0.11 ± 0.027^{a}	0.14 ± 0.112^{a*§}	0.11 ± 0.000^{a}	0.05 ± 0.033^{a*}
Chlorophyll *a* (mg m^{-3})	33.0 ± 3.80^{a}	95.2 ± 50.88^{a*}	38.1 ± 0.00^{a}	47.9 ± 15.33^{a§}
BOD_2 (mg l^{-1})	2.9 ± 0.46^{a}	6.8 ± 1.92^{a*}	3.2 ± 0.00^{a}	4.5 ± 0.84 ^{a§}

Variable	**Farm C[2]**		**Farm D[3]**	
	Intake	*Discharge*	*Intake*	*Discharge*
Total Nitrogen (mg l^{-1})	0.83 ± 0.000^{a}	0.76 ± 0.050^{a§}	0.47 ± 0.000^{a}	0.57 ± 0.065^{a†}
Total Ammonia-N (mg l^{-1} NH_3-N)	0.10 ± 0.000^{a}	0.06 ± 0.010^{b*}	0.04 ± 0.000^{a}	0.05 ± 0.020^{a*}
Oxidized N (mg l^{-1} NO_2-NO_3-N)	0.22 ± 0.000^{a}	0.010 ± 0.003^{b*}	0.003 ± 0.000^{a}	0.002 ± 0.001^{a*}
Total phosphorus (mg l^{-1})	0.23 ± 0.000^{a}	0.22 ± 0.08^{a§}	0.04 ± 0.000^{a}	0.04 ± 0.003^{a†}
Sol. reactive phosphate (mg l^{-1} PO_4-P)	0.15 ± 0.000^{a}	0.21 ± 0.063^{a§}	0.004 ± 0.000^{a}	0.002 ± 0.001^{a†}
Chlorophyll *a* (mg m^{-3})	34.1 ± 0.00^{a}	25.7 ± 2.09^{b§}	13.1 ± 0.00^{a}	14.4 ± 2.90^{a†}
BOD_2 (mg l^{-1})	4.2 ± 0.00^{a}	3.4 ± 0.23^{b§}	1.2 ± 0.00^{a}	2.0 ± 0.26^{a†}

ab Means with the same superscript designation are not significantly different ($P > 0.05$). Horizontal comparisons only within farm.
*†§ Means followed by the same symbol are not significantly different ($P > 0.05$). Horizontal comparisons only among farm discharges.
1 Farm A is located on a riverine estuary.
2 Farm B and C are located on a different riverine estuary.
3 Farm D is located on an embayment of the Gulf of Fonseca.

Total nitrogen, total ammonia-nitrogen, total phosphorus, and soluble reactive phosphorus concentrations did not differ significantly between pond intake and discharge water on individual farms (Table 3). Intake water had significantly greater oxidized nitrogen concentrations than discharge waters on farms B and C (Table 3). Significantly greater chlorophyll *a* and BOD_2 concentrations were detected in intake water on farm C (Table 3). Total ammonia-nitrogen and oxidized nitrogen concentrations in discharge water did not differ significantly among farms (Table 3). Concentrations of all other water quality variables in discharge water generally were significantly greater on farm A, intermediate on farms B and C, and significantly lower on farm D (Table 3). No significant relationship was detected between total quantity of feed added per pond and concentration of any nutrient in discharge water. Among farms, chlorophyll *a* and BOD_2 concentrations in pond water were independent of total ammonia-nitrogen concentration ($r^2 = 0.034$, $P = 0.509$ and $r^2 = 0.006$, $P = 0.789$, respectively) and soluble reactive phosphorus concentration ($r^2 = 0.005$, $P = 0.800$ and $r^2 = 0.010$, $P = 0.726$, respectively).

Discussion

Comparison of shrimp production data among farms was not possible because of the unexpectedly high shrimp mortality; 25% survival of the stocked populations had been expected. Differences among farms, if they exist, would only become evident once the shrimp biomass had attained the critical standing crop. Both shrimp yield and mean final weight were significantly correlated with survival, which varied significantly among ponds. Shrimp yields in the present experiment were 17 to 58% of rainy season yields reported for Taura Syndrome-affected ponds in Honduras (Teichert-Coddington et al., 1996; Teichert-Coddington et al., 1997). Production data from farm A, the farm where PD/A CRSP production research is implemented, were intermediate to results from the other farms.

Feed conversion ratios were very high for this experiment because shrimp in ponds were overfed. The computer-generated feed curve incorporated the expected mortality (75% of stocked animals) but, because mortality exceeded anticipated levels by 27%, feed inputs were overestimated. While it is impossible to make inferences regarding farm effects on FCRs, these results clearly demonstrate the difficulty in achieving efficient feed management in ponds affected by Taura Syndrome.

No differences were detected in total nitrogen concentrations in pond effluent among farms during weekly water exchange events even though nitrogen was added as feed to ponds. Although high FCRs indicated that feed was wasted and not consumed by shrimp, pond water quality did not appear to be affected significantly. However, observed nutrient concentrations in discharge water (measured as total nitrogen, total phosphorus, chlorophyll *a*, and BOD_2) were higher than in intake water, which indicates a net discharge of nutrients. As has been reported previously (Teichert-Coddington et al., 1996; Teichert-Coddington et al., 1997), weekly exchange events discharged organic-rich water to estuaries. Inorganic nitrogen and phosphorus entering ponds was converted to organic matter that was discharged to estuaries. Nutrient loads in pond effluents were lower on farm D (located in an embayment of the Gulf of Fonseca) probably because of the lower nutrient content of intake water (Teichert-Coddington, 1995).

Anticipated Benefits

This study was designed to evaluate shrimp growth, yield, and survival in similarly managed ponds on four different commercial farms in southern Honduras. Data would provide information on expected results when PD/A CRSP-developed management systems were implemented on other farms in the region. However, because shrimp survival only was 20% of the expected value, it was impossible to evaluate among farm variability, which is unfortunate given the major logistical effort required for this experiment. This experiment should be repeated if producers are interested and willing to make facilities available again.

Acknowledgments

This study was made possible by collaboration of the Dirección General de Pesca y Acuicultura, Secretaría de Agricultura y Ganadería, República de Honduras, and shrimp producers of the Honduran National Association of Aquaculturists (ANDAH). Jaime López assisted in the laboratory, and Gustavo Flores assisted in the field.

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South America

To evaluate the aquaculture potential of local and native species and to develop appropriate culture technologies, CRSP researchers from Southern Illinois University at Carbondale and the Instituto de Investigaciones de la Amazonia Peruana and the Universidad Nacional de la Amazonia Peruana are comparing the survival, growth, standing crop at harvest, condition, feed conversion, and cost of production of two species indigenous to the Orinoco and Amazon Rivers—*Colossoma macropomum* and *Piaractus brachypomus*. Production trials of *P. brachypomus*, called paco in Peru, are planned to be completed within the period of the Eighth Work Plan. Beginning in April 1997 fingerlings were stocked in earthen ponds at densities of 3,000 and 4,000 fish ha^{-1} and water quality data and preliminary production results are presented in this report.

Development of Sustainable Pond Aquaculture Practices for *Piaractus brachypomus* in the Peruvian Amazon

Eighth Work Plan, Peru Research 1 (PR1)

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Introduction

A need exists to evaluate the aquaculture potential of local and native species, and to develop appropriate culture technologies. *Piaractus brachypomus*, native to the Orinoco and Amazon Rivers (Goulding, 1982), is an important food fish in the Amazon basin. However, little production technology has been developed and published. In addition, there has been inadequate attention to economic analyses, such as determinations of cost of production. Such information is critical for the sustainable development of this new aquaculture species.

Presently the available broodstocks are generally taken from the natural environment although some have been produced in aquaculture stations. The fish are captured as fry, fingerlings, juveniles, or adults and are then stocked in culture ponds and prepared as future broodstock. The selection of broodstock is made on the basis of external characteristics during the spawning season. Only in Brazil and Panama do culturists select broodstock based on individual performance (growth rate, quantity and quality of semen, fertilization rate, fry production, etc.).

No standardization exists for stocking densities of fry or fingerlings (Campos, 1993). Likewise, no uniform fish diets are available in the region (Cantelmo et al., 1986; Ferraz de Lima and Castagnolli, 1989). This project will determine the stocking densities necessary to efficiently and economically rear *Piaractus brachypomus* to marketable size (approximately 1 kg). Replicated pond studies will be carried out in Iquitos at the Instituto de Investigaciones de la Amazonia Peruana (IIAP) pond facility. Pond water quality and effluents will be monitored.

Methods and Materials

Initially *Colossoma macropomum* was the focal species of this study; however, due to a spawning failure, *Piaractus brachypomus* was substituted for the first year study, as approved by the PD/A CRSPs Technical Committee co-chairs. *Piaractus brachypomus* could not be obtained until March 1997 and were at an advanced fingerling size. Consequently, the fry production aspect of the study was precluded in the first year. The fingerling production trial commenced 29 April 1997.

Site Characterization

Eighteen ponds at the Quistacocha Aquaculture Station of the Institute for the Investigation of the Peruvian Amazon were mapped and measured. Ponds range from 60 to 5320 m^2. Eighteen ponds are also available at the University of the Peruvian Amazon Quistacocha Fish Culture Station. These ponds range in size from 20 to 596 m^2. Soil and water samples were collected from representative ponds at both stations and sent to Dr. Claude Boyd at Auburn University for analysis. Preliminary studies on water quality parameters have been initiated. More detailed analyses await equipment currently being held in customs in Lima, Peru.

Table 1. Feed ingredients and costs in U.S. dollars.

Ingredient	Percent in Diet	Cost per Unit
Fish Meal	19.9	1.00 kg^{-1}
Soybean	19.9	0.72 kg^{-1}
Wheat	19.9	0.26 kg^{-1}
Rice	29.8	0.19 kg^{-1}
Corn Meal	9.9	0.68 kg^{-1}
Vitamin C	0.1	32.00 kg^{-1*}
Vitamin/Mineral Premix	1.0	
Fish Oil	0.5	1.60 kg^{-1}

* Cost reflects price of vitamin C and vitamin/mineral premix combined.

Six ponds, ranging in size from 1,015 to 5,320 m^2, were stocked with *Piaractus brachypomus* at two densities; three ponds at 3,000 fish ha^{-1} and three ponds at 4,000 fish ha^{-1}. The mean initial weight was 27.5 g with the exception of one replicate pond of the lower density treatment where the initial mean weight was 4.0 g. Data will be collected from this replicate, but will not be used in the density comparisons. A locally manufactured feed was given to ponds (see Table 1 for feed composition and cost). The study commenced 29 April 1997 and will continue for approximately seven months. General water quality parameters (hardness, dissolved oxygen, temperature, conductivity, ammonia-nitrogen, carbon dioxide, pH, alkalinity, nitrite-nitrogen, and nitrate-nitrogen) are being analyzed; however, detailed analyses have not commenced because equipment purchased for the project is halted in customs.

Results

First month production and water quality results are summarized in Tables 2 and 3.

Wild caught *Colossoma*, 4 to 12 g in size are sold to fish farmers for $100 US per 1,000 fish. Hatchery production at IIAP costs $70 US per 1,000 fish 4 to 12 g in size; fingerling production cost includes broodstock maintenance, labor, food, and fertilization. IIAP sells fingerlings and establishes the price for the wild catch.

Table 2. Weight gain and feed conversion efficiency of *Piaractus brachypomus* cultured at two densities in Iquitos, Peru, from 29 April to 30 May 1997 (n = number of ponds).

Density	Mean			n
	Initial Weight (g)	*Weight Gain (g)*	*Feed Conversion Efficiency (%)*	
3,000 fish ha^{-1}	27.5	41.4	103.9	2
4,000 fish ha^{-1}	27.5	48.4	121.9	3

Pond construction estimates were made by the Ministry of Fisheries. Estimates were made for machine- and hand-construction of levees and include land clearing, levee construction, pipes, and fencing. Cost of purchasing land is not included. Total costs are lower for machine-constructed ponds ($1,960 US) than for manually-constructed ponds ($2,700 US). The levee is 30 m in length; 2 m wide at the top; 9.5 m at the base; and 2.5 m in height. The surface area of pond water is 3,000 m^2.

Discussion

It is too early in the study to draw conclusions. Fish are feeding well and water quality should improve as the addition of organic material in the form of excess feed and fish feces accumulates in the ponds. More detailed production cost data are being collected.

Table 3. Ranges for water quality parameters taken at midday, Iquitos, Peru (May 1997).

Parameter	Range
Hardness	20
Dissolved oxygen (mg l^{-1})	3.2-7.8
T_{min}/T_{max} (°C)	26.5-32.0
Conductivity (mS cm^{-1})	80-150
Ammonia-nitrogen (mg l^{-1})	<1.0
Carbon dioxide (mg l^{-1})	6-20
pH	5.6-6.9
Alkalinity (mg l^{-1})	20
Nitrite-Nitrogen (mg l^{-1})	0.09-0.12
Nitrate-Nitrogen (mg l^{-1})	0.15-0.25

Anticipated Benefits

The development of aquaculture techniques for the culture of *Piaractus brachypomus* will benefit many sectors throughout the Peruvian Amazon. Sustainable aquaculture offers rural farmers an alternative source of food and/or income in addition to agricultural production and will provide a steady supply of high quality protein in the marketplace. *Piaractus brachypomus*, a native species, along with *Colossoma* play a crucial role in disseminating seeds in the flooded rainforests. The culture of this species should relieve some commercial fishing pressure.

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East Africa

Research at the Sagana Fish Culture Station addressed the Reproduction Control and Feeds and Fertilizers themes. Three investigations—site development, experimentation to determine the variability of sex ratio inheritance of the Turkana strain of *Oreochromis niloticus*, and a study to determine the nutritional contribution of supplemental feeds to tilapia production—were delayed and will overlap with the period of the Ninth Work Plan. A pilot study to test two preservation methods, using stable isotope analysis was completed as planned.

As a result of pond renovation efforts, the Sagana site is now equipped with 12 experimental ponds and five fingerling production ponds. Four of the station's quarter-acre ponds were put into production after an extended period of disuse. Additionally, the station's main water supply canal was lined with concrete to prevent erosion.

Researchers at the Sagana site also collaborated in an effort to produce monosex male tilapia through androgenesis by identifying strains of tilapia that produce progeny with uniform and predictable sex ratios. Initial tests are studying variations in the sex ratio inheritance of the Turkana strain of *Oreochromis niloticus*. This particular strain originated from a stock of *O. niloticus* that was isolated in a crater lake located on an island of Lake Turkana, Kenya.

A second research focus at Sagana is the determination of the relative contribution of supplemental feed and inorganic fertilizers to tilapia production. Stable carbon isotopic analysis will be used to assess the nutritional contribution of natural and supplemental foods to production of Nile tilapia. A pilot study was conducted at the University of Arkansas at Pine Bluff to determine whether two techniques for sample preservation—lyophilization and fixation in a mixture of formalin and alcohol—differentially affected the carbon isotope ratios of plankton and tilapia. The carbon isotopic ratios were significantly different for plankton; for tilapia results were not significantly different. Study findings indicated that either lyophilization or chemical preservation with formalin and alcohol are viable preservation techniques for isotopic analysis; however, lyophilization may be the preferred technique because chemical irritants are avoided, shipping costs are lower, and the variability of isotope ratios is slightly lower using this preservation technique.

New Site Development and Characterization

Eighth Work Plan, Kenya Research 1 (KR1)

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Abstract

The resident researcher arrived at the Sagana Fish Culture Farm on 31 March 1997 and pond renovation was begun on 10 April. Four of the farm's one-acre ponds were split into twelve experimental ponds and five fingerling production ponds. Activities to complete renovation through July 1997 included drain pipe installation, inlet reinforcement, and planting grass on levees. Several of the renovated ponds still require some excavation to ensure that depths and bottom contours are uniform among all experimental ponds. Each of the new experimental ponds will have a surface area of 800 m^2 and minimum and maximum water depths of 60 and 100 cm, respectively. The ponds have sufficient freeboard so that water levels may be raised to achieve maximum depths of 120 cm and surface areas of 825 m^2. Part of the earthen main water supply canal was lined with concrete.

Four of the farm's quarter-acre ponds were put into production after an extended period of disuse. Site development and characterization activities to be completed through September and October 1997 include: upgrading the chemistry laboratory; obtaining laboratory, farm, and office supplies, a datalogger system, and a four-wheel-drive vehicle; and characterizing the site in terms of soil, water, and climatic attributes.

Strain Variations in Sex Ratio Inheritance

Eighth Work Plan, Kenya Research 2 (KR2)

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Abstract

The sex ratio of individual spawns has been studied in only a limited number of strains of *Oreochromis niloticus*. Although *O. niloticus* females are thought to be homogametic and males heterogametic, progeny of single pair spawns have not conformed to the expected 50:50 sex ratio inheritance. The variance in *O. niloticus* sex ratio inheritance may be related to strain differences. Pair spawning and grow-out of the Turkana strain of Nile tilapia *(O. niloticus vulcani)* is being conducted at the Sagana Fish Culture Farm. This strain originated from a stock isolated in a crater lake on an island in Lake Turkana, Northern Kenya.

In the current study, the sex ratio of each set of progeny with a minimum of 100 fish will be determined though gonadal examination. Spawning hapas were constructed and stocked between three and five times between February and June, 1997. When water temperatures were less than 24 °C, females were often killed by males. Bird predation on brood fish also contributed to losses. Of the five spawns obtained, survival of fry was very low, due to predation from insects, and no spawns resulted in fry numbers greater than 30. More spawning hapas will be constructed and protection against predators will be enhanced to obtain improved spawning results. Sex ratio data from each spawn will be analyzed by Chi square to determine whether it differs from the expected 50:50 inheritance. This research is carried out in conjunction with the Eighth Work Plan study "Monosex Tilapia Production Through Androgenesis." For initial study results refer to the report entitled "Artificial Propagation of Nile Tilapia for Chromosome Manipulation" in the Global Research section of this report.

Nutritional Contribution of Natural and Supplemental Foods for Nile Tilapia: Stable Carbon Isotope Analysis (Effect of Preservation Method on Stable Carbon Isotope Ratios of Plankton and Tilapia)

Eighth Work Plan, Kenya Research 3A (KR3A)

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Introduction

Stable carbon isotope analysis is a useful technique to obtain quantitative estimates of the relative contributions of different food sources to the nutrition of aquatic animals in ponds (Schroeder, 1983; Anderson et al., 1987; Lochmann and Phillips, 1996).

In the present study, stable carbon isotopic analysis will be used to obtain quantitative estimates of the contribution of natural and supplemental feeds to the nutrition of tilapia in ponds in Sagana, Kenya. This can be accomplished by comparing the carbon isotopic "signatures" of tilapia with their known and probable food sources. The assumption underlying the technique is that the fish isotopic profiles will resemble that of the food(s) they assimilate most. The results may indicate how feeding/fertilization practices can be adjusted to minimize feed costs while maximizing fish production.

Here we report the results of a pilot study that was conducted at the University of Arkansas at Pine Bluff to determine whether different methods of sample preservation (chemical versus lyophilization) affect the carbon isotope ratios of fish and plankton differently.

Methods and Materials

Three tilapia (*Oreochromis niloticus*) and three plankton samples were collected from commercial ponds in Arkansas. Individual fish were collected by dipnet and each plankton sample was obtained by filtration of 100 ml of pond water through a glass filter (47 mm diameter, 1 micrometer pore size) (Gelman Sciences). Fish were sacrificed by a blow to the head and divided longitudinally into halves. Each half was homogenized to uniform consistency. Each plankton sample was also divided into two equal portions. One half of each fish and plankton sample was fixed in 10% buffered formalin for 48 h, soaked for 24 h in deionized water to remove formalin, then preserved in 70% isopropyl alcohol (APHA, 1995). The second half of each sample was preserved by freeze-drying. All preserved samples were sent to a commercial laboratory (Coastal Science Laboratories, Inc.) for stable carbon isotope analysis using a micromass isotope ratio mass spectrometer (Anderson et al., 1987).

Results

The carbon isotopic ratio of plankton preserved in formalin and alcohol was significantly different to that of plankton preserved by freeze-drying (Table 1). Results did not differ for tilapia tissue preserved in formalin and alcohol versus freeze-drying (Table 1).

Discussion

From the standpoint of isotopic analysis, either lyophilization or chemical preservation would be suitable for further use in this study because the magnitude of the preservation effect was small compared to the trophic enrichment (diet) effect expected over the experimental period. However, freeze-drying is preferred (when feasible) because noxious chemicals are not used, samples do not have to be shipped in liquid, (which reduces shipping costs), and because the variability in isotope ratios

Table 1. Results of pilot study: comparison of stable carbon isotope ratios ($\delta^{13}C$) of tilapia and zooplankton samples preserved either chemically or by lyophilization.

Sample Type: Plankton (n = 3 for each treatment)	
$\delta^{13}C$ (‰) *Formalin/alcohol*	$\delta^{13}C$ (‰) *Lyophilized*
-25.1	-24.6
-24.9	-24.7
-25.2	-24.6
Mean ± SD	Mean ± SD
-25.1 ± 0.15	-24.6 ± 0.06
(ANOVA, Fisher's LSD, *P* = 0.01)	

Sample Type: Tilapia, Whole, Ground (n = 3 for each treatment)	
$\delta^{13}C$ (‰) *Formalin/alcohol*	$\delta^{13}C$ (‰) *Lyophilized*
-21.9	-21.7
-21.2	-21.6
-21.9	-20.7
Mean ± SD	Mean ± SD
-21.7 ± 0.38	-21.3 ± 0.58
(ANOVA, Fisher's LSD, *P* = 0.41)	

of freeze-dried samples was slightly lower than that of chemically-preserved samples.

Although lyophilization is an excellent way to prepare samples for isotope analysis, freeze-drying equipment is not always accessible at CRSP project sites. This study indicates that chemical preservation of samples would also be an appropriate method of sample preparation prior to isotope analysis.

Anticipated Benefits

The results of this study indicate that freeze-drying is a more reliable method of preserving samples for isotope analysis than is formalin and alcohol preservation. The lyophilization technique will be used at the Sagana site, and possibly in other CRSP experiments to preserve samples to allow the estimation of the relative contribution of different food sources to tilapia nutrition.

Acknowledgments

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Southeast Asia

Research in Southeast Asia emphasized the Pond Dynamics, Feeds and Fertilizers, Environmental Effluents, and Aquaculture Systems Modeling themes. The schedule for a study regarding the minimization of the environmental impacts of pond draining will be completed within the period of the Eighth Work Plan. Philippines research to develop low cost supplemental feeds for tilapia in pond and cage culture is progressing according to schedule.

The CRSP research presented in this report covers the continued refinement of an integrated culture system, the evaluation of harvest techniques in terms of environmental impacts, the development of two bioenergetics growth models, and the assessment of supplemental diets for the culture of tilapia. Researchers in Thailand have developed a "tilapia-tilapia cage cum pond" integrated rotational culture system in which large Nile tilapia are stocked in cages suspended in earthen ponds while smaller Nile tilapia are stocked outside the cages in the open pond to utilize cage wastes. The smaller tilapia are then harvested from the open pond, stocked in cages, and cultured until they reach marketable size (>500 g). Production using the integrated rotational culture system produced >500 g Nile tilapia in a 90-day culture period; however, there was not sufficient phytoplankton production to support the growth of the smaller open-pond tilapia.

In a follow-up experiment, the biomass of stocked caged tilapia was increased to address the insufficiency of natural food for the open-pond tilapia. Experiments were then conducted to test an alternative method for increasing tilapia biomass in ponds and maintaining water quality suitable for tilapia production. Additional cages were suspended in ponds, and the effects of aeration were examined.

The mean weight of caged tilapia did not achieve market size in these experiments, and mean individual weight and survival of tilapia in cages decreased significantly with an increased number of cages in ponds. Feed conversion ratios were significantly lower in the treatments with one and two cages suspended in ponds compared with ponds containing three and four cages. Daily weight gain of open-pond tilapia increased as the number of cages suspended in ponds increased. Combined growth performance measures of caged and open-pond tilapia were significantly higher for aerated ponds than non-aerated ponds. Aeration significantly improved the growth performance of caged tilapia; however, the growth rate of open pond tilapia significantly declined in aerated ponds. Survival and net yield of open-pond tilapia was also significantly lower in aerated ponds in comparison with non-aerated ponds.

A second research emphasis focused on the environmental effects of aquaculture. To minimize the environmental impacts of effluents discharged from ponds and manage pond drainage so that nutrients are retained in the pond system, CRSP researchers in Thailand designed a study composed of five treatments to evaluate and compare 1) the amount of nitrogen (N), phosphorus (P), and solids discharged during pond draining and 2) fish harvest techniques designed to reduce loading of nutrients and solids in effluent waters. For treatment A ponds, which were not drained, tilapia were partially anaesthetized with tea seed cake and seined three times. In both treatments B and C, ponds were completely drained and the fish harvested from a harvest pit. Treatments B and C differed in that treatment B ponds were limed with calcium hydroxide 24 hours before harvesting. In both treatments D and E, ponds were drawn down to 50 cm, seined twice, then completely drained, the difference being that treatment D ponds were filled with the water that had previously been used in treatment E ponds. (Treatments D and E took place sequentially, with treatment E taking place before treatment D.)

Treatments D and E discharged a large amount of waste. Under the treatment D management regime, the amount of waste discharged from a 1-ha pond would be equivalent to 1.1 t BOD_5, 142 m^3 settleable matter, 34.1 t total solids, 3.8 t total volatile solids, 26.5 to total suspended solids, 2.8 t volatile suspended solids, 93 kg nitrogen, and 9.5 kg total phosphorus. Adoption of the harvest techniques utilized in treatments in B and C instead of the harvest technique of treatment D would result in the following reductions in effluent levels: 47% of BOD_5, 80% of settleable matter, 51% of total solids, 45% of total volatile solids, 74% of total suspended solids, 66% of volatile suspended solids, and 37% of total nitrogen. Researchers in Thailand also found that reusing drainage water to fill empty ponds was another way to reduce the impacts of effluents discharged from ponds. Sediment deposition in this study occurred at a rate of 6.3 ± 1.0 cm over a four month culture period. Over time ponds must be drained because of sediment accumulation. CRSP scientists in Thailand suggest that ponds be drained every four to five years so that the environmental effects associated with the discharge of waste products are minimized and the excessive accumulation of sediment is avoided.

Special Topics Research in Thailand entailed the development of two bioenergetics growth models—one that simulated the growth of both caged and open-pond Nile tilapia in a cage-cum-pond integrated rotational culture system and a second that linked Nile tilapia growth with the limiting nutrients in a pond system. Both of the bioenergetics growth models incorporated five key variables: body size, temperature, dissolved oxygen, unionized ammonia, and food availability. The bioenergetics growth model for the integrated culture system was designed so that caged tilapia were provided artificial feed, and the growth of the open-pond fish was solely fortified by the primary productivity of the pond system. Results of model simulations revealed that if cages were stocked with less than 200 fish pond $^{-1}$, phosphorus limited primary production at the beginning of the experiment (nitrogen became the limiting nutrient as time progressed) with consequent declines in the growth of open-pond tilapia. The model also showed that biological nitrogen fixation accounted for 44.2% to 74.8% of the total nitrogen available for primary production. Additionally, sensitivity analysis revealed that caged tilapia affected the growth of open-pond tilapia but not vice versa; however, reduced caged tilapia growth and increased open-pond tilapia growth did correlate with reductions in water quality. The model linking tilapia growth with limiting nutrients in ponds used a relative feeding level parameter—a function of net primary productivity based on limiting nutrients and the standing crop of Nile tilapia. The model successfully detected growth variations among ponds receiving the same nitrogen and phosphorus inputs and revealed that variations were caused by carbon, which limited primary productivity from 55 to 99% of the culture period. Sensitivity analysis also indicated that parameters for net energy due to feeding were more sensitive than the fasting catabolism parameter. Furthermore, the sensitivity analysis showed that growth was most sensitive to food availability parameters when dissolved oxygen (DO) was above its critical limit (1.0 mg l^{-1}). Growth was most sensitive to metabolic factors when DO was below its critical limit.

Supplemental feeds are used when the natural productivity of a culture system cannot support the aquaculturist's expected level of fish production and are not intended to provide complete nutrition but rather to contribute nutrients that otherwise would be limiting to fish growth. Providing protein in supplemental feeds may be a way to improve growth rates; however, protein supplementation is expensive. Numerous studies have attempted to identify inexpensive sources of protein through the examination of plants, agricultural processing wastes, and even brewery wastes.

In the Philippines identifying effective, inexpensive supplemental feeds is a research focus of relevance. CRSP researchers from the University of Arizona and Central Luzon State University, Philippines, initiated a study that will test the viability of yeast and composted rice straw as ingredients in supplemental feeds and will compare and assess the use of compression pelleting technology versus meat grinding equipment to form feeds. Historically, yeast was too costly to use as a dietary protein supplement although recently its potential has been reconsidered because new bioreactor technology has lowered its cost. Rice straw, an agricultural by-product, could also be used in the formulation of supplemental diets, but it is not high in protein. Composting is a solution that may address the low protein content of straw. Microbes convert the straw from a material high in indigestible matter to microbial biomass that is digestible for tilapia. The feeds will be tested both in conventional pond systems and in cages suspended in ponds. For the first two and one half months, the fish will depend on the algal productivity of ponds for food. When the fish begin to receive the prepared feed, it will be at a rate of 5% BW during the first two months; during the final month prior to harvest, the fish will be fed at a rate of 3% BW.

In collaboration with the extensive outreach activities of the Asian Institute of Technology, PD/A CRSP research was directed toward identifying supplemental feeds that would improve fish growth rates for aquaculturists in Vietnam. Traditionally, freshwater fish culture systems in Vietnam involved the extensive polyculture of Chinese carps, but a growing demand for fish in domestic markets has provided an impetus for aquaculturists to intensify their production systems. In 1994 Nile tilapia (*Oreochromis niloticus*) were imported to Vietnam, and, due to their rapid growth and attractive appearance, tilapia culture has steadily gained in popularity. Still, there are difficulties associated with tilapia culture in Northern Vietnam. Farmers have encountered problems with overwintering the ponds; harvesting fish before winter requires that farmers manage their systems for rapid growth in a limited culture period. Supplemental feeding in fertilized ponds is one possible method for improving growth rates. Currently in Vietnam, most fish farmers use rice bran as fish feed. Because information is scarce regarding the economic returns of this feeding practice, CRSP researchers from the Asian Institute of Technology have implemented a two-part study that 1) focuses on the selection of supplemental diets and 2) determines the economically optimal feeding rates for the selected diets. In part I of the study conducted in North Vietnam, Nile tilapia (*O. niloticus*) of the Chitralada strain were cage cultured in earthen ponds, and nine supplemental diets were evaluated. The diets were formulated with chicken feed or fish meal containing varying levels of protein content and mixed with corn meal, cassava meal, or rice bran.

There were no significant differences in water quality for the supplemental diets tested. Tilapia fed the supplemental diet containing 20% crude protein formulated from chicken concentrated feed and mixed with cassava meal was superior in terms of growth rates and had the highest profit (US $0.34 kg^{-1} produced fish), but this diet had a relatively high total feed investment per unit of cultured area. Trends in growth rate data indicated that diets using chicken concentrated feed rather than fish meal as the main source of protein resulted in faster growth rates and higher fish production. This trend may be attributable to the micronutrients added to the feeds by the producers. Diets mixed with rice bran resulted in slower rates of growth than the diets mixed with cassava or corn meal. Economic comparisons indicated that the use of formulated feeds was preferable to the use of single ingredients (i.e., corn meal or rice bran). The sole use of rice bran or corn meal resulted not only in low fish production and profits but also high breakeven prices. For farmers that require a lower investment per unit of cultured area with a relatively high net profit and returns to investment, research suggests diets formulated from fish meal and mixed with cassava or corn meal or diets formulated from chicken concentrated feed and mixed with rice bran. These findings demonstrate that tilapia culture in fertilized ponds, under the conditions present in the study area, is a profitable enterprise if the appropriate supplemental diets are selected.

A Finishing System for Large Tilapia

Interim Work Plan, Thailand Activity 4

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Introduction

The major production system for Nile tilapia (*Oreochromis niloticus*) is semi-intensive with inorganic or organic fertilizer inputs in earthen ponds. However, interest in the cage culture of tilapia has increased, particularly in tropical, developing countries (Coche, 1982). Caged fish are commonly fed with high protein diets; wastes from the caged tilapia in the form of dissolved nutrients, uneaten feed, and metabolic products, either directly or indirectly released into the surrounding pond environment, cause accelerated eutrophication (Beveridge, 1984; Ackefors, 1986; Lin et al., 1989). Fish-livestock integrated systems have been practiced widely for centuries (Pillay, 1992). Therefore, it has been suggested that wastes from cage culture could also serve as a valuable resource in an integrated aquaculture system by generating natural foods for filter-feeding species such as Nile tilapia (Lin et al., 1989; Lin, 1990; McGinty, 1991; Yi et al., 1996).

A series of experiments was designed to develop a tilapia-tilapia cage-cum-pond integrated rotation culture system. Large Nile tilapia were stocked in cages suspended in earthen ponds while small Nile tilapia were stocked outside the cages in the open pond. The open-pond fish utilize cage wastes and can be transferred from the open pond to restock the cages. Large Nile tilapia (> 500 g) can fetch a much higher price in some countries than the smaller Nile tilapia (250-300 g) that are commonly produced in fertilized pond systems. Caged Nile tilapia, in a tilapia-tilapia cage-cum-pond integrated culture system, have been grown to 500 g within 90 days (stocked at 50 fish m^{-3} with one cage per 335-m^2 pond of 1.0 to 1.2-m water depth) (Yi et al., 1996). However, the wastes derived from the single cages were insufficient to generate abundant natural foods for the growth of the open-pond fish.

Increasing the biomass of caged tilapia should increase the nutrients available for the growth of open-pond tilapia. However, increasing the stocking densities within single cages has been found to lower overall fish production (Yi et al., 1996). An alternative strategy is to increase the number of cages within a pond. The current experiment tested the use of multiple cages in ponds, and the use of water aeration to reduce the risk of oxygen depletion (Boyd, 1990). The objectives of this study were to determine the appropriate biomass of large tilapia in cages required to support maximum production of small tilapia in open water, and also to investigate the effects of aeration on water quality and growth performance of both caged and open-pond tilapia.

Methods and Materials

Two experiments were conducted for 90 days (January-April 1985) and 84 days (July-September 1995) at the Asian Institute of Technology (AIT) in Thailand. Large tilapia (91 ± 5.2 to 103 ± 4.6 g) were stocked in 4-m^3 net cages (50 fish m^{-3}) suspended in earthen ponds. One, two, three, or four cages were suspended in each earthen pond as experimental treatments. Tilapia fingerlings (13 ± 0.3 to 16 ± 1.3 g) were stocked at two fish m^{-3} in the open water of all ponds four days after the cages were stocked. Both caged and open-pond Nile tilapia were hormone-treated, sex-reversed males that had received methyltestosterone treatment in the fry stage.

The first experimental trial was conducted in a randomized complete block design in twelve ponds. Eight ponds measured 335 m^2 surface area with a water depth of 1.2 m, and four ponds measured 394 m^2 surface area with a water depth of 1 m. The water volume of all ponds was similar (approximately 330 m^3). The ponds were divided into three blocks, with each block containing ponds of similar dimensions. One replication from each treatment was randomly assigned to one pond in each block. Metal frame cages (2 x 2 x 1.2 m) covered with 2-cm mesh nylon net were suspended to a depth of 1 m in each pond. In the shallower ponds, an area of nine m^2, below each cage, was deepened by 20 cm to keep the cage floors 20 cm from the pond bottom.

The cages were arranged within ponds as follows: for the one-cage treatment each cage was placed in the center of a pond; for the two-cage treatment, cages were placed at either end of each pond along the pond central line, 2 m from the pond bottom edges; for the three-cage treatment, one cage was placed in the middle of each pond and the other two were placed in the opposite corners of the pond, 2 m from the pond bottom edges, and the other two were placed in the opposite corners of the pond, 2 m from central lines; for the four-cage treatment, cages were arranged in the four corners of each pond, 2 m from bottom lines. To confine floating pellets within the cages, a fine mesh polyethylene net was fixed from 5 cm above to 15 cm below the water surface on the outside of each cage. A wooden or bamboo walkway connected each cage to the pond bank. To prevent fish from jumping between the cages and the pond, and to protect fish from predation by birds, the cages were covered with nylon nets.

Water was added weekly to replace losses due to seepage and evaporation. No fertilizer was applied to any experimental pond so that the growth of open-pond tilapia was solely dependent on natural foods derived from cage wastes. Caged tilapia were fed with commercial floating pellets (30% crude protein, Charoen Pokphand Co., Ltd.) at 0900 and 1600 h, six days per week. Feeding rates were 3%, 2.5%, and 2% body weight per day (BWD) during the first, second, and third month, respectively. The feed ration was adjusted daily based on mortality and the biweekly sample weight of caged tilapia. Small tilapia stocked in open water were not given artificial feed.

Average weights of tilapia were determined biweekly by bulk weighing 10% of tilapia from each cage in addition to 40 open-pond tilapia per pond. Caged tilapia were sampled by dip net and open-pond tilapia by seine. Tilapia were harvested, counted, and bulk weighed at the end of the experiments.

To estimate total nitrogen and phosphorus loading from cages to open water, resulting from caged-tilapia waste products, the nitrogen (N) and phosphorus (P) content of carcasses of caged tilapia (harvested and dead) was deducted from the N and P content of the feed input.

Water column samples were taken biweekly near the center of each pond at approximately 0900 h for the analysis of pH, total ammonia-nitrogen, chlorophyll *a*, total suspended solids and total volatile solids (APHA, 1985). Values for pH and temperature were used to determine the amount of unionized ammonia-nitrogen in ponds (see conversion table in Boyd, 1990). Temperature and DO were measured between 0600 and 0700, and between 1500 and 1600 h with an oxygen meter (YSI model 54).

Due to high mortality (65.5-70.5%) of tilapia in all cages of one replicate of the four-cage treatment, and due to the low levels of DO recorded, a second experiment was conducted to examine the effect of nighttime aeration on the growth performance of tilapia in this cage-cum-pond integrated culture system. An aeration trial was conducted from July through September 1995 in three ponds, similar to the ponds of the first experiment. Four cages, similar in dimensions and stocking density to the first experiment, were placed in each pond. A paddle-wheel aerator (0.75 kW and 1,400 rpm) was mounted at the mid-point of the long side of each pond. Ponds were aerated from 0300 to 0800 h daily.

Due to unavailability of sufficient ponds, controls could not be run concurrently with this second experiment. Data from the four-cage treatment in the first experiment provided control data (the two non-aerated ponds that did not experience high mortality). The comparison of data collected at different times of the year can be justified because the results of other experiments conducted from August to November 1994, from January to April, and from July to September 1995 showed no apparent effects of temperature on the growth performance of either caged or open-pond tilapia. Water temperature in each culture cycle only briefly fell outside the optimum range for tilapia growth (Yi, 1997).

Data were analyzed statistically by analysis of variance and regression (Steele and Torrie, 1980) using the Statgraphics 7 statistical software package. Differences were considered significant

Table 1. Growth performance of male Nile tilapia stocked in cages at 50 fish m^{-3} in treatments with one, two, and three cages per pond.

Performance Measures		Treatments (cages per pond)		
		1	*2*	*3*
STOCKING				
Total Wt.	(kg $cage^{-1}$)	18.7 ± 1.4	18.6 ± 0.7	18.2 ± 1.0
Mean Wt.	(g $fish^{-1}$)	94 ± 6.8	93 ± 3.7	91 ± 5.2
HARVEST				
Total Wt.	(kg $cage^{-1}$)	95.6 ± 6.9^{a}	67.1 ± 1.8^{b}	43.7 ± 12.7^{c}
Mean Wt.	(g $fish^{-1}$)	478 ± 34.6^{a}	341 ± 10.6^{b}	280 ± 32.0^{c}
Total Wt. Gain	(kg $cage^{-1}$)	76.9 ± 5.8^{a}	48.5 ± 1.7^{b}	25.5 ± 13.2^{c}
Mean Wt. Gain	(g $fish^{-1}$)	384 ± 28.9^{a}	248 ± 9.6^{b}	189 ± 34.7^{c}
	(g $fish^{-1}$ d^{-1})	4.27 ± 0.32^{a}	2.75 ± 0.11^{b}	2.10 ± 0.39^{c}
Net Yield	(g m^{-3} d^{-1})	213.6 ± 16.0^{a}	134.6 ± 4.6^{b}	70.7 ± 36.7^{c}
	(kg $cage^{-1}$ $crop^{-1}$)	76.9 ± 5.8^{a}	48.5 ± 1.7^{b}	25.4 ± 13.2^{c}
	(kg $pond^{-1}$ $crop^{-1}$)	76.9 ± 5.8	96.9 ± 2.7	76.3 ± 34.7
	(t ha^{-1} $crop^{-1}$)	2.30 ± 0.17	2.89 ± 0.08	2.34 ± 1.19
Survival	(%)	100.0 ± 0.0^{a}	98.5 ± 2.1^{a}	76.8 ± 15.9^{b}
FCR		1.22 ± 0.06^{a}	1.64 ± 0.05^{ab}	3.01 ± 1.27^{c}
Gross Yield	(kg $pond^{-1}$ $crop^{-1}$)	95.6 ± 6.9	134.2 ± 1.7	131.1 ± 32.2
	(t ha^{-1} $crop^{-1}$)	2.86 ± 0.21	4.00 ± 0.05	3.97 ± 1.11

[abc] Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

at an alpha of 0.05. All means are presented with ± 1 standard error (SE).

Results

Effects of the Biomass of Caged Nile Tilapia

Mean individual weight of harvested caged tilapia decreased significantly ($P < 0.05$) from 478 ± 34.6 to 280 ± 32.0 g as the number of cages in a pond increased (Table 1). During grow-out, the weight of tilapia increased steadily with a mean daily weight gain ranging from 2.10 ± 0.39 to 4.27 ± 0.32 g $fish^{-1}$ (Figure 1); mean daily weight gain decreased as the number of cages in ponds increased . The mean daily weight gain in the treatment with one cage was significantly higher than the other treatments with two or three cages. Survival of caged tilapia also decreased significantly from 100 ± 0.0% to 76.8 ± 15.9% with an increase in the number of cages. The net yield of tilapia in a cage decreased significantly ($P < 0.05$) from 76.9 ± 5.8 to 25.4 ± 13.2 kg $cage^{-1}$ $crop^{-1}$ with an increase in the number of cages. However, there were no significant ($P > 0.05$) differences in total net yield, which ranged from 76.9 ± 5.8 to 96.9 ± 2.7 kg $pond^{-1}$ $crop^{-1}$ for all treatments with caged tilapia. The highest total net yield was achieved in the two-cage treatment. Feed conversion ratios in the one- and two-cage treatments were significantly lower (1.22 ± 0.06 and 1.64 ± 0.05) than in the three-cage treatment (3.01 ± 1.27).

The biomass of caged tilapia also had significant ($P < 0.05$) effects on the growth, net yield, and survival of open-pond tilapia. There were no significant differences in survival of open-pond tilapia between the two- and three-cage treatments; however, survival in the two- and three-cage treatments was significantly higher than in the one-cage treatment. Mean individual weight and net yield increased with an increase in the number of cages (Table 2). The mean weight of individual

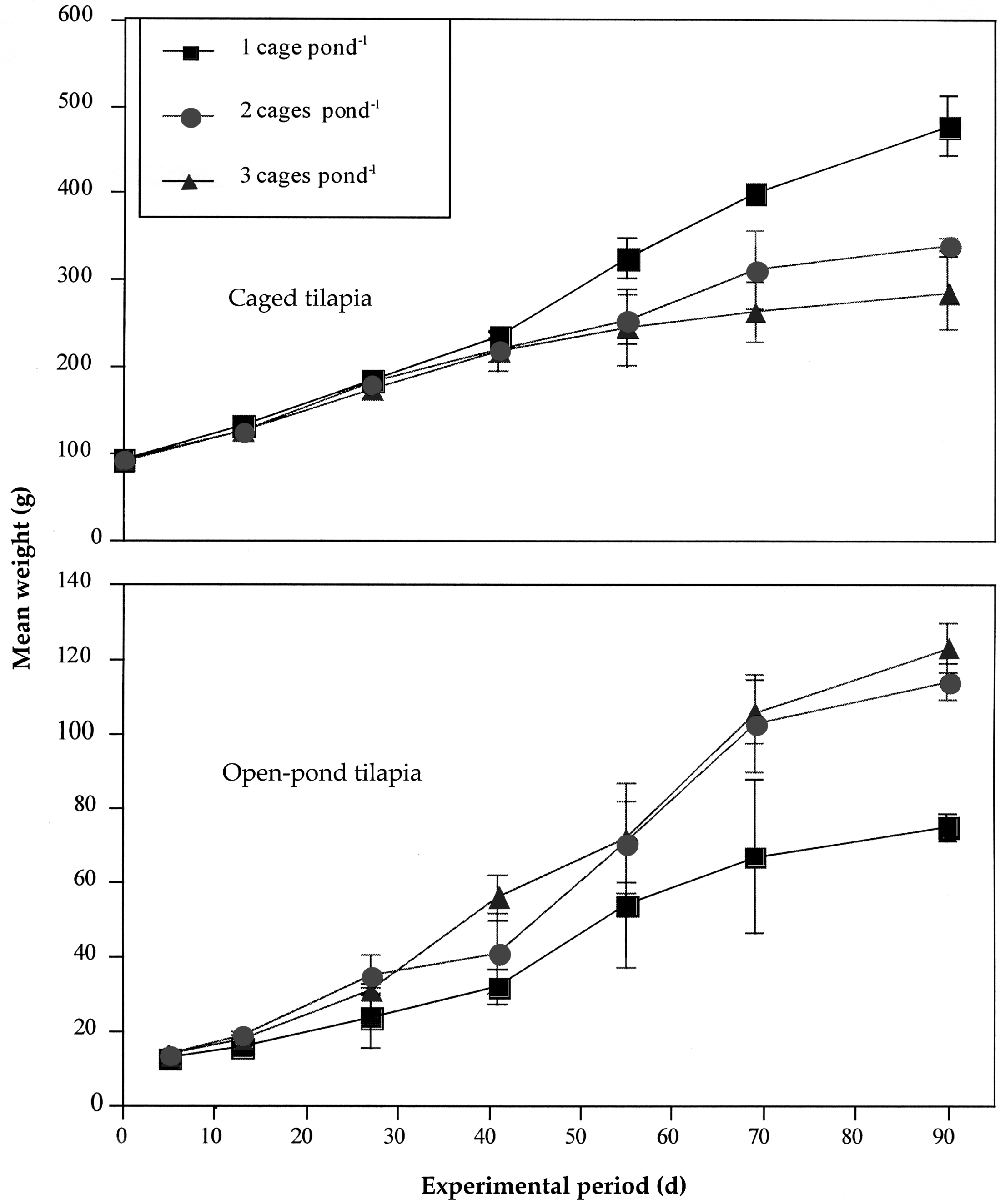

Figure 1. Growth of caged and open-pond Nile tilapia stocked in treatments with one, two, and three cages per pond.

fish in the one-cage treatment (75 ± 3.6 g) was significantly lower than in the two- and three-cage treatments (114 ± 5.0 and 123 ± 6.5 g, respectively; see Table 2 and Figure 1); however, there was no significant difference in mean individual weight between the two- and three-cage treatments. The daily weight gain of open-pond tilapia was significantly different among treatments; weight gain increased with the number of cages per treatment. Total weight gain of open-pond tilapia was positively correlated ($r = 0.95$, $P < 0.01$) with total feed input to cages (Figure 2). Cage wastes fertilized the ponds at rates of 0.92, 1.76, and 2.36 kg N ha^{-1} d^{-1} giving N:P ratios of 5.01, 4.64, and 4.47 for treatments with one, two, and three cages, respectively. The extrapolated net yield of open-pond tilapia increased significantly from 1.10 ± 0.05 t ha^{-1} $crop^{-1}$

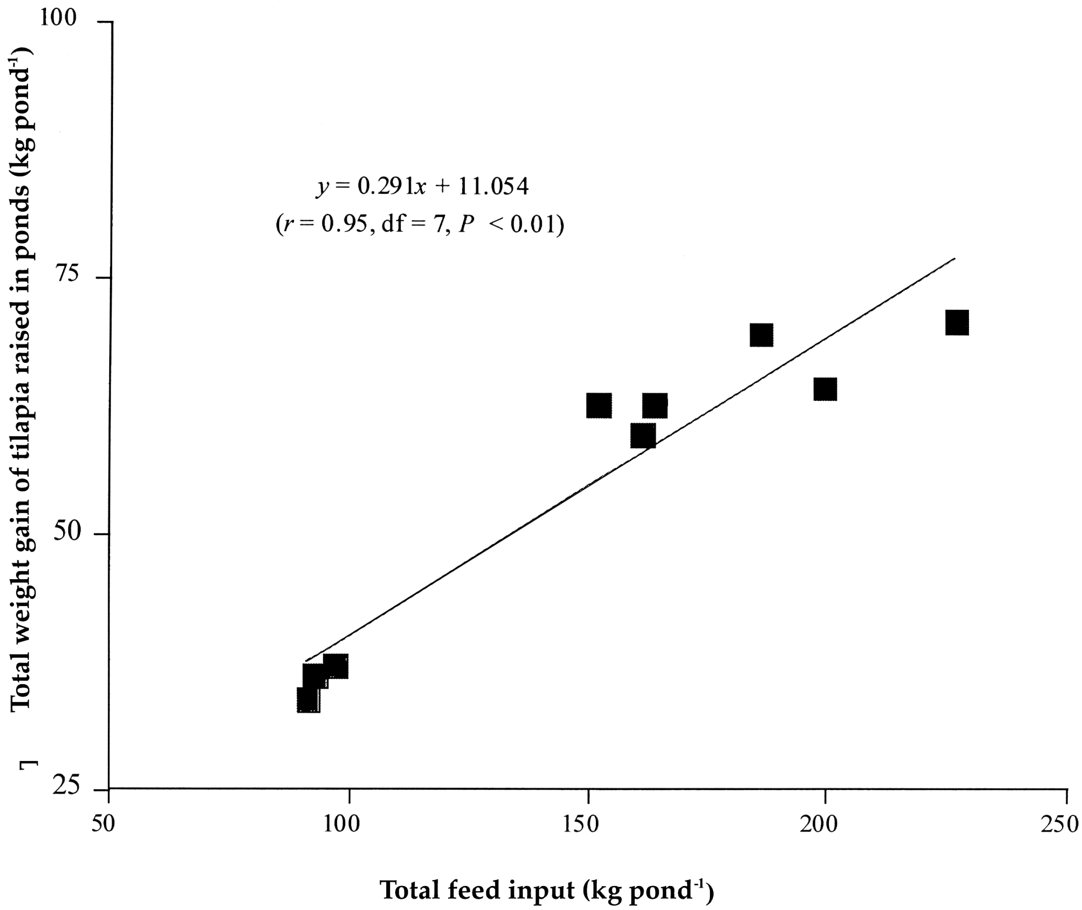

Figure 2. Relationship between total feed given to caged Nile tilapia and total weight gain of open-pond Nile tilapia.

for the one-cage treatment to 1.93 ± 0.06 and 2.14 ± 0.12 t ha^{-1} $crop^{-1}$ in the two- and three-cage treatments, respectively.

The extrapolated net yield from the two-cage treatment for caged and open-pond tilapia combined was 4.83 ± 0.03 t ha^{-1} $crop^{-1}$; this yield was not significantly higher ($P > 0.05$) than the yields from the one- and three-cage treatments (3.39 ± 0.22 and 4.41 ± 1.10 t ha^{-1} $crop^{-1}$, respectively) (Table 3). The overall FCRs were 0.83 ± 0.03 and 1.00 ± 0.03 for the one- and two-cage treatments, respectively. These FCRs were not significantly different from each other, but they were significantly better than the FCR for the three-cage treatment (1.43 ± 0.19).

Water temperature averaged 28.7°C and pH ranged from 6.8 to 7.9 throughout the experimental period. The measured DO concentrations at dawn for all treatments decreased sharply over the first month and then gradually to approximately 1 mg l^{-1}. The DO concentrations tended to be higher, but were not significantly different, in the treatments with a lower biomass of caged tilapia (Figure 3). The unionized NH_3-N concentration in the one-cage treatment was significantly lower than in the two- and three-cage treatments (Figure 3). The phytoplankton standing crop, as indicated by chlorophyll *a* concentrations, was generally low, but chlorophyll *a* concentration was significantly higher in the three-cage treatment than in the one- and two-cage treatments (Figure 3).

Effects of Aeration

Aeration improved the growth performance of caged tilapia significantly ($P < 0.05$) (Table 4). The survival of caged tilapia increased from 93.9 ± 2.6% in non-aerated ponds to 97.3 ± 2.2% in the aerated ponds. The mean weight of caged tilapia harvested from aerated ponds (403 ± 36.3 g) was significantly greater than that from non-aerated

Table 2. Growth performance of open-pond, male Nile tilapia stocked in ponds at two fish m^{-3} with either one, two, or three cages per pond.

Performance Measures		**Treatments (cages per pond)**		
		1	*2*	*3*
STOCKING				
Total Wt.	(kg $pond^{-1}$)	8.6 ± 0.2	9.0 ± 0.5	0.9 ± 0.4
Mean Wt.	(g $fish^{-1}$)	13 ± 0.3	14 ± 0.8	14 ± 0.6
HARVEST				
Total Wt.	(kg $pond^{-1}$)	45.5 ± 1.8[b]	73.8 ± 1.7[a]	80.5 ± 3.9[a]
Mean Wt.	(g $fish^{-1}$)	75 ± 3.6[b]	114 ± 5.0[a]	123 ± 6.5[a]
Total Wt. Gain	(kg $pond^{-1}$)	36.9 ± 1.6[b]	64.8 ± 2.0[a]	71.6 ± 3.7[a]
Mean Wt. Gain	(g $fish^{-1}$)	62 ± 3.4[b]	100 ± 5.2[a]	109 ± 6.1[a]
	(g $fish^{-1}$ d^{-1})	0.72 ± 0.03[b]	1.16 ± 0.06[a]	1.27 ± 0.07[a]
Net Yield	(t ha^{-1} $crop^{-1}$)	1.10 ± 0.05[b]	1.93 ± 0.06[a]	2.14 ± 0.12[a]
Survival	(%)	89.7 ± 2.2[b]	94.6 ± 2.4[a]	95.5 ± 1.1[a]
Gross Yield	(t ha^{-1} $crop^{-1}$)	1.36 ± 0.06[b]	2.20 ± 0.05[a]	2.40 ± 0.12[a]

[ab] Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

ponds (261 ± 19.5 g) (Table 4 and Figure 4). The net yield of caged tilapia in aerated ponds reached 232.0 ± 25.7 kg $pond^{-1}$ $crop^{-1}$ compared with the yield in non-aerated ponds which reached 122.0 ± 10.6 kg $pond^{-1}$ $crop^{-1}$. Feed conversion ratios were 1.30 ± 0.12 and 2.08 ± 0.02, respectively.

The growth rate of open-pond tilapia was, however, significantly lower ($P < 0.05$) in aerated ponds (1.21 ± 0.08 g $fish^{-1}$ d^{-1}) than in non-aerated ponds (1.50 ± 0.14 g $fish^{-1}$ d^{-1}). The final mean individual weights for aerated and non-aerated ponds were 113 ± 7.1 and 142 ± 11.3 g, respectively (Figure 4). The survival of open-pond tilapia in aerated ponds (90.4 ± 2.2%) was significantly lower than the survival of open-pond tilapia in non-aerated ponds (96.2 ± 1.3%). The net yield of open-pond tilapia in aerated ponds was also significantly lower than in non-aerated ponds (Table 5).

Pooled growth performance measures of both caged and open-pond tilapia were significantly higher ($P < 0.05$) for aerated ponds than for non-aerated ponds (Table 6). The extrapolated net yield was significantly higher for aerated ponds (8.62 ± 0.78 t ha^{-1} $crop^{-1}$) than for non-aerated ponds (6.19 ± 0.53 t ha^{-1} $crop^{-1}$), giving overall FCRs of 1.04 ± 0.06 and 1.25 ± 0.01, respectively.

Water temperature averaged 29.0°C and pH ranged from 6.8 to 8.0 throughout the experimental period. DO concentration at dawn in non-aerated ponds decreased sharply from an initial level of 5.27 mg l^{-1} to less than 1.00 mg l^{-1} over the first two months; DO was less than 1.00 mg l^{-1} for the remainder of the experiment. DO concentration in the aerated ponds was 1.47 mg l^{-1} at the beginning of the experiment prior to aeration, but once aeration was initiated DO ranged from 3.30 to 4.83 mg l^{-1} throughout the experiment (Figure 5). Unionized NH_3-N concentrations in aerated ponds increased from 0.00 to 0.10 mg l^{-1} over 90 days, while the concentrations in non-aerated ponds fluctuated from 0.01 to 0.05 mg l^{-1} throughout the experiment (Figure 5). The phytoplankton standing crop was nearly the same in both aerated and non-aerated treatments; chlorophyll *a* concentrations increased in both treatments but were higher in non-aerated ponds than in aerated ponds at the end of the experiment (Figure 5). The levels of total suspended solids increased gradually in both aerated and

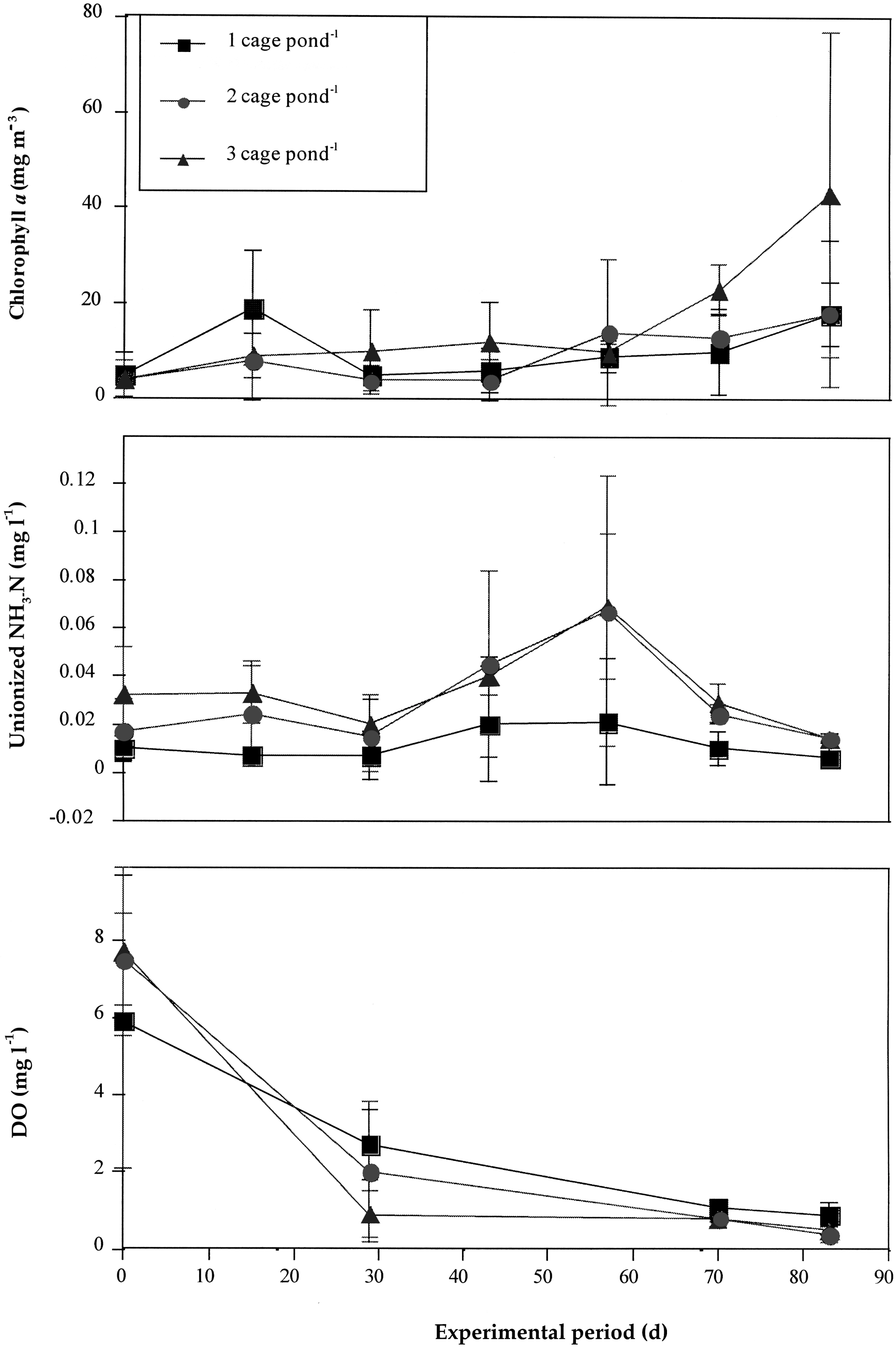

Figure 3. Fluctuations in DO at dawn, unionized NH_3 (0900 h), and chlorophyll *a* (0900 h) in treatments with one, two, and three cages per pond.

Table 3. Growth performance of male Nile tilapia cultured in ponds stocked with two fish m^{-3} from treatments with either one, two, or three cages per pond.

Performance Measures		Treatments (cages per pond)		
		1	*2*	*3*
Initial Fish Biomass	(kg)	27.3 ± 1.5	27.3 ± 1.5	63.6 ± 2.3
Final Fish Biomass	(kg)	141.1 ± 8.5	208.0 ± 0.9	211.5 ± 33.7
Fish Biomass Gain	(kg)	113.8 ± 7.2	161.8 ± 1.1	147.9 ± 35.8
Net Fish Yield	(g m^{-3} d^{-1})	3.83 ± 0.25	5.45 ± 0.04	4.98 ± 1.22
	(t ha^{-1} $crop^{-1}$)	3.39 ± 0.22	4.83 ± 0.03	4.41 ± 1.10
Gross Fish Yield	(t ha^{-1} $crop^{-1}$)	4.21 ± 0.26	6.21 ± 0.03	6.31 ± 1.02
Overall FCR		0.83 ± 0.03[a]	1.00 ± 0.03[a]	1.43 ± 0.19[b]

[ab] Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

Table 4. Growth performance of male Nile tilapia stocked in four cages in aerated and non-aerated ponds.

Performance Measures		Treatments	
		Aerated	*Non-aerated*
STOCKING			
Total Wt.	(kg $cage^{-1}$)	20.6 ± 0.9	18.5 ± 0.5
Mean Wt.	(g $fish^{-1}$)	103 ± 4.6	92 ± 2.8
HARVEST			
Total Wt.	(kg $cage^{-1}$)	78.6 ± 8.6[a]	49.0 ± 4.3[b]
Mean Wt.	(g $fish^{-1}$)	403 ± 36.3[a]	261 ± 19.5[b]
Total Wt. Gain	(kg $cage^{-1}$)	58.0 ± 8.0[a]	30.5 ± 4.0[b]
Mean Wt. Gain	(g $fish^{-1}$)	300 ± 33.6[a]	169 ± 17.9[b]
	(g $fish^{-1}$ d^{-1})	3.57 ± 0.40[a]	1.88 ± 0.20[b]
Net Yield	(g m^{-3} d^{-1})	172.6 ± 24.1[a]	84.7 ± 11.0[b]
	(kg $pond^{-1}$ $crop^{-1}$)	232.0 ± 25.7[a]	122.0 ± 10.6[b]
	(t ha^{-1} $crop^{-1}$)	6.93 ± 1.03[a]	3.65 ± 0.30[b]
Survival	(%)	97.3 ± 2.2	93.9 ± 2.6
FCR		1.30 ± 0.12[a]	2.08 ± 0.02[b]
Gross Yield	(kg $pond^{-1}$ $crop^{-1}$)	314.4 ± 31.4[a]	196.0 ± 9.6[b]
	(t ha^{-1} $crop^{-1}$)	9.39 ± 1.10	5.85 ± 0.28

[ab] Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

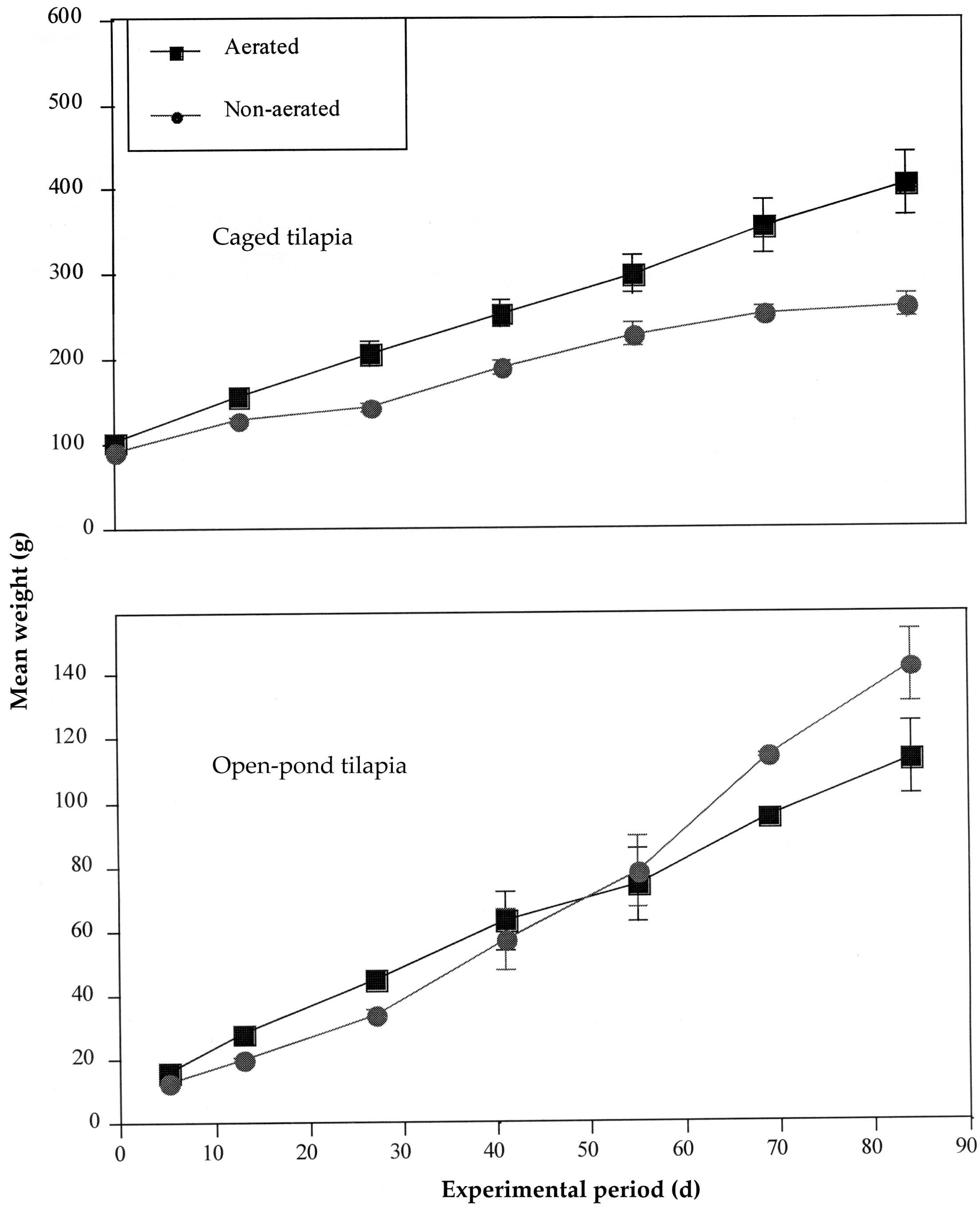

Figure 4. Growth of caged and open-pond Nile tilapia in aerated and non-aerated treatments with four cages per pond.

Table 5. Growth performance of male Nile tilapia stocked at two fish m^{-3} in treatments with four cages, in aerated and non-aerated ponds.

Performance Measures		Treatments	
		Aerated	*Non-aerated*
STOCKING			
Total Wt.	(kg $pond^{-1}$)	10.5 ± 0.9	8.7 ± 0.4
Mean Wt.	(g $fish^{-1}$)	16 ± 1.3	13 ± 0.6
HARVEST			
Total Wt.	(kg $pond^{-1}$)	67.3 ± 2.6^{b}	94.0 ± 6.3^{a}
Mean Wt.	(g $fish^{-1}$)	113 ± 7.1^{b}	142 ± 11.3^{a}
Total Wt. Gain	(kg $pond^{-1}$)	56.8 ± 2.1^{b}	85.3 ± 6.7^{a}
Mean Wt. Gain	(g $fish^{-1}$)	97 ± 6.3^{b}	129 ± 12.0^{a}
	(g $fish^{-1}$ d^{-1})	1.21 ± 0.08^{b}	1.50 ± 0.14^{a}
Net Yield	(g m^{-3} d^{-1})	2.15 ± 0.08^{b}	3.08 ± 0.23^{a}
	(t ha^{-1} $crop^{-1}$)	1.70 ± 0.07^{b}	2.55 ± 0.21^{a}
Survival	(%)	90.4 ± 2.2^{b}	96.2 ± 1.3^{a}
Gross Yield	(t ha^{-1} $crop^{-1}$)	2.01 ± 0.09^{b}	2.81 ± 0.19^{a}

^{ab} Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

Table 6. Growth performance of male Nile tilapia cultured in ponds stocked at two fish m^{-3} in treatments with four cages, in aerated and non-aerated ponds.

Performance Measures		Treatments	
		Aerated	*Non-aerated*
Initial Fish Biomass	(kg)	92.9 ± 2.9	82.7 ± 1.4
Final Fish Biomass	(kg)	381.7 ± 34.5	290.2 ± 15.9
Fish Biomass Gain	(kg)	288.8 ± 32.7^{a}	207.5 ± 17.3^{b}
Net Fish Yield	(g m^{-3} d^{-1})	10.42 ± 1.18^{a}	7.49 ± 0.62^{b}
	(t ha^{-1} $crop^{-1}$)	8.62 ± 0.78^{a}	6.19 ± 0.53^{b}
Gross Yield	(t ha^{-1} $crop^{-1}$)	11.39 ± 0.84^{a}	8.66 ± 0.48^{b}
Overall FCR		1.04 ± 0.06^{a}	1.25 ± 0.01^{b}

^{ab} Mean values with different superscript letters in the same row are significantly different ($P < 0.05$).

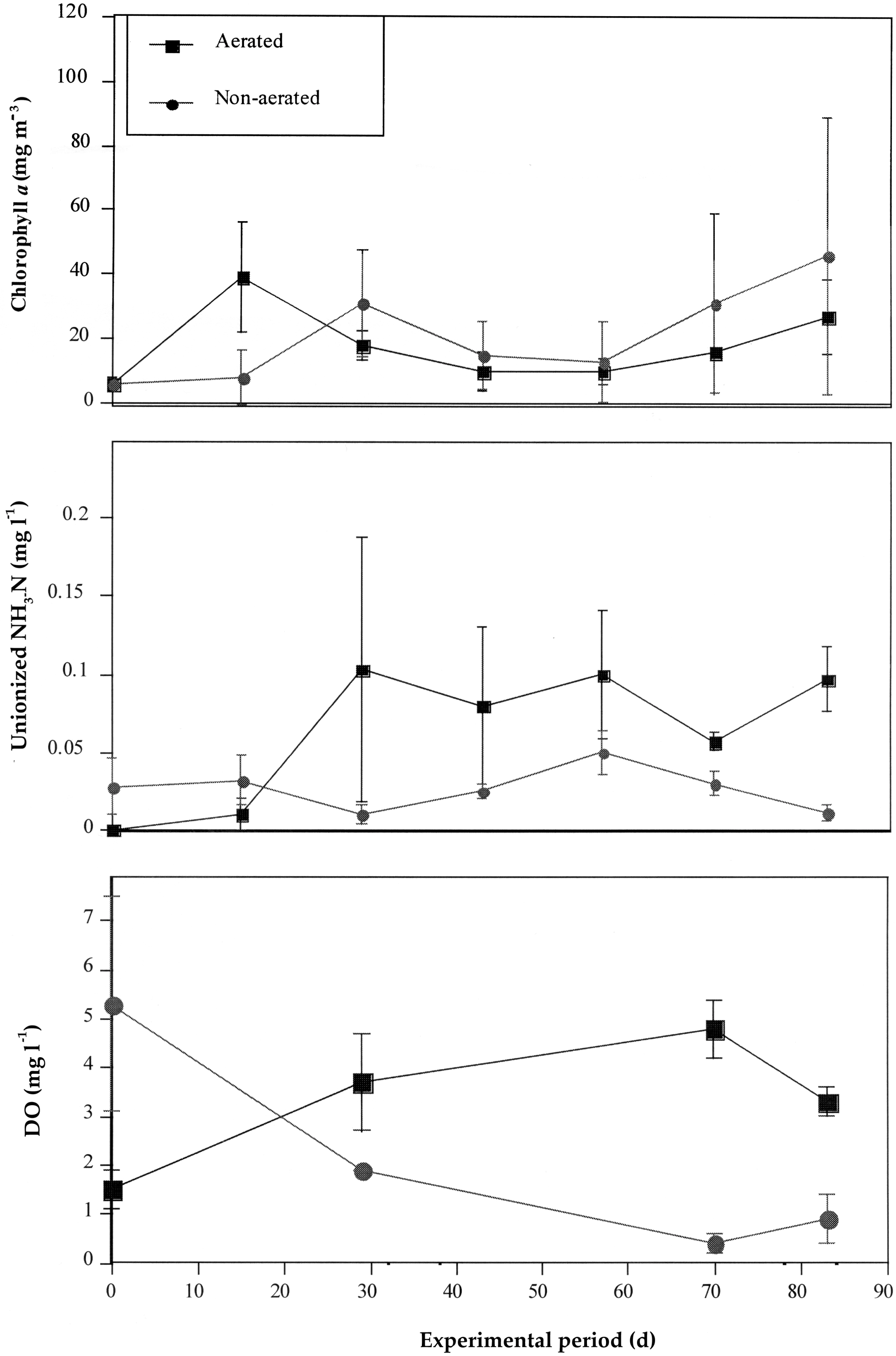

Figure 5. Fluctuations in DO at dawn, unionized NH_3 (0900 h), and chlorophyll *a* (0900 h) in aerated and non-aerated treatments with four cages per pond.

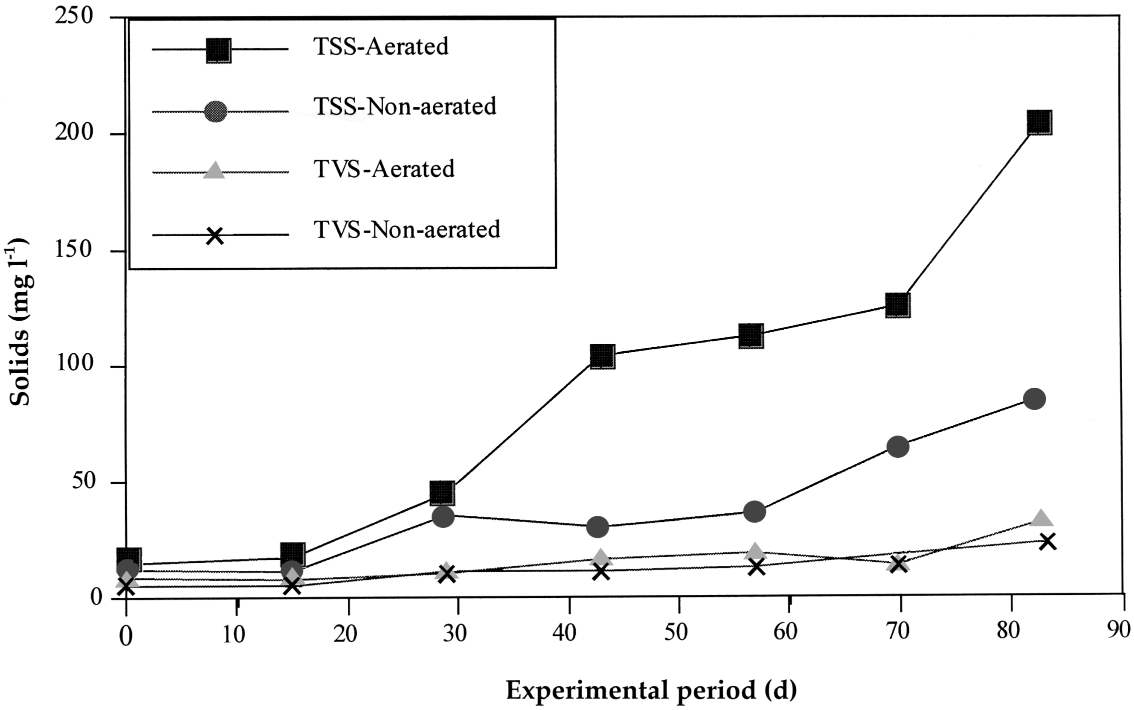

Figure 6. Comparison between concentrations of TSS and TVS in aerated and non-aerated ponds.

non-aerated ponds prior to aeration. The levels of total suspended solids increased dramatically in aerated ponds, after aeration, compared to non-aerated ponds, and there was no significant difference in total volatile solids between aerated and non-aerated ponds (Figure 6).

Discussion

The mean weight (478 ± 34.6 g) of caged tilapia in this experiment did not reach the desired market size (> 500 g). This may have been due to the initial stocking size of caged tilapia (94 ± 6.8 g) in the one-cage treatment which was smaller than the initial stocking size in an experiment that did produce market-size tilapia (Yi et al., 1996) (148 ± 2.5 g). The mean daily weight gain in the present experiment was similar to the results of Yi et al. (1996). The lower daily weight gains in the two- and three-cage treatments were due to the higher biomass of caged tilapia. Daily weight gains in this study, which ranged from 2.10 ± 0.39 to 2.75 ± 0.11 g fish^{-1}, were higher than those of cage studies carried out by Guerrero (1979, 1980) or for tilapia reared in thermal effluent by Philippart et al. (1979, cited by Coche, 1982) where daily weight gains ranged from 0.56 to 1.60 g fish^{-1}. The daily weight gain in the present study is comparable to growth in ponds obtained by McGinty (1991) (2.09 to 2.49 g fish^{-1}) or to growth in intensively-cultured cages in lakes (1.05 to 2.33 g fish^{-1}) (Coche, 1977 and Campbell, 1978, cited by Coche, 1982).

The FCR in three-cage treatment was higher than the FCR for the treatments with fewer cages as a result of relatively higher mortality and lower growth rates during the grow-out period. FCRs of the one- and two-cage treatments were similar to the one-cage treatment with the same stocking densities in an earlier experiment (Yi et al., 1996). FCRs obtained in this study were also similar to FCRs reported by Carro-Anzalotta and McGinty (1986) for intensive cage culture in ponds, but were much lower than FCRs reported by Guerrero (1979, 1980) and McGinty (1991) for culture in ponds and by Coche (1977, cited by Coche, 1982) and Campbell (1978, cited by Coche, 1982) for lakes. The above results indicate that a higher biomass of caged tilapia in a pond negatively affects growth performance.

The reason for significantly lower survival of open-pond tilapia in the one-cage treatment was not clear. The survival of open-pond tilapia in the two-, three- and four-cage treatments in non-aerated ponds was greater than 90%. Survival and growth of open-pond tilapia was not influenced by poor water quality as was the growth and survival of caged tilapia. This may have been due to the differing requirements and tolerances to water quality. Fish contained at high densities in cages, in contrast to free-swimming fish in earthen ponds, are unable to seek out zones of favorable water quality and may be more susceptible to fluctuations in pond water quality, particularly to low concentrations of DO (Hargreaves et al., 1991). Instantaneous changes in water quality in cages, especially after feeding in late afternoon, in addition to accumulated cage wastes may cause a sudden decline in water quality around cages.

Daily weight gains of open-pond tilapia, which increased with the increased biomass of caged tilapia in this experiment, were much higher than daily weight gains from a previous experiment (Yi et al., 1996), but were still lower than daily weight gains obtained from catfish-tilapia cage-cum-pond integrated culture (2.4 to 2.7 g fish^{-1}) (Lin, 1990) and tilapia-tilapia cage-cum-pond integrated culture (2.31 g fish^{-1}) (McGinty, 1991). This is probably due to the lower feed input to cages and a higher stocking density of open-pond tilapia used in the present experiment. The poor growth performance of open-pond tilapia in Yi et al.'s (1996) experiment may have been caused by the relatively large initial stocking size of tilapia. Growth may have been stunted when the tilapia were held in fertilized ponds at high density for about three months prior to the experiment. In the present experiment treatments with a higher biomass of caged tilapia produced more wastes which improved the growth of open-pond tilapia.

The nitrogen loading rates derived from caged tilapia, ranging from 0.92 to 2.36 kg ha^{-1} d^{-1}, were lower than the optimal fertilization rates (approximately 4 kg N ha^{-1} d^{-1}) recommended for semi-intensive culture of tilapia in tropical ponds (Knud-Hansen et al., 1991). However, the extrapolated gross yields of open-pond tilapia from this experiment increased significantly from 5.44 ± 0.18 t ha^{-1} yr^{-1} in the one-cage treatment to 8.80 ± 0.14 and 9.60 ± 0.35 t ha^{-1} yr^{-1} in the two- and three-cage treatments, respectively. These yields surpassed yields obtained from catfish-tilapia cage-cum-pond integrated culture systems (Lin, 1990), conventional integrated fish-livestock systems (AIT, 1986), and systems optimally fertilized with either chicken manure (Diana et al., 1988) or chemical fertilizers (Diana et al., 1991). In the present experiment, open-pond tilapia depended solely on the wastes (dissolved nutrients from feed, metabolic wastes and uneaten feed) derived from cages. Uneaten feed, knocked out of the cages as a result of the vigorous swimming activity of caged tilapia (Collins, 1971; Coche, 1979; McGinty, 1991) provided open-pond tilapia with some supplemental feed. This may explain why open-pond tilapia in this experiment demonstrated better growth performance than tilapia cultured in traditionally fertilized ponds, despite the lower fertilization rates. However, as evidenced by the very low FCR of caged tilapia, the amount of uneaten feed was probably limited. This may imply that dissolved nutrients from feed and metabolic wastes of caged tilapia are in a more utilizable form or are in more efficient supply than from organic manure or chemical fertilizers.

The combined extrapolated net yields of caged and open-pond tilapia ranged from 13.56 ± 0.41 to 19.32 ± 0.10 t ha^{-1} yr^{-1} in the one-, two-, and three-cage treatments. They were much higher than yields achieved in the earlier experiment (6.5 to 9.7 t ha^{-1} yr^{-1}) (Yi et al., 1996), primarily because the growth performance of open-pond tilapia in this experiment was better. The higher stocking density of open-pond tilapia in the present experiment also resulted in higher yields (approximately 5.2 to 6.6 t ha^{-1} yr^{-1}) than in the tilapia-tilapia cage-cum-pond integrated culture system reported by McGinty (1991).

The higher mortality in treatments with a higher biomass of caged tilapia may have been caused by an extended period of exposure to low DO concentrations. Extended periods of hypoxia may reduce growth (Chervinski, 1982) and cause mortality (Coche, 1982). Net yield of all caged tilapia leveled off when the number of cages in ponds increased or the biomass of caged tilapia increased, which indicates that the carrying capacity of caged tilapia, in the earthen ponds stocked with small tilapia at two fish m^{-3}, may have been exceeded. High numbers of open-pond tilapia caused a decrease in the growth of caged tilapia (McGinty, 1991), therefore lowering the stocking density of open-pond tilapia may be the best way to increase the harvest size of both caged and open-pond tilapia.

Significantly higher gross yields and better feed efficiencies were found in aerated ponds compared to non-aerated ponds. Similar results were obtained in channel catfish ponds (Lai-Fa and Boyd, 1988). The survival of caged tilapia in aerated ponds was also similar to survival rates in aerated channel catfish ponds (Hollerman and Boyd, 1980). Growth performance of caged tilapia was much better in aerated ponds than in non-aerated ponds. This was probably due to the higher DO concentrations of aerated ponds at dawn throughout the experimental period. However, daily weight gain of caged tilapia in aerated ponds was lower than in non-aerated treatments with one cage, and the final mean weight of caged tilapia in aerated ponds did not reach the desired size (> 500 g). This was probably due to the smaller stocking size (103 ± 4.6 g) and shorter grow-out period (84 days) than in Yi et al.'s, (1996) experiment (141 ± 11.1 to 152 ± 2.1 g and 90 days, respectively). The aeration experiment was terminated 6 days earlier than planned because of the threat of a flood. Another reason for the lower growth rates might be the three-week delay of aeration at the beginning of this experiment due to technical problems, and a power outage that lasted 24 hours near the end of the experiment. However, aeration for five hours each night prevented nighttime DO concentrations from falling below 3 mg l^{-1}. Since DO concentrations were adequate (Boyd, 1990), some other water quality parameters, probably ammonia, imposed limits on production. Teichert-Coddington and Green (1993) reported that total ammonia-nitrogen concentrations were significantly higher in aerated treatments than in non-aerated controls. Boyd (1990) found that total ammonia-nitrogen concentrations of 1 to 3 mg l^{-1} were common in aerated ponds with high feeding rates and that sublethal effects of ammonia probably adversely affected fish growth. The total ammonia-nitrogen concentrations in aerated ponds in this experiment averaged 1.83 to 2.56 mg l^{-1} after the first month and probably caused the lower growth of caged tilapia in aerated ponds compared to treatments with lower biomass of caged tilapia in the present and previous experiments (Yi et al., 1996). Water exchange has been shown to improve high ammonia concentrations in channel catfish ponds (Parker, 1979; Plemmons and Avault, 1980); however, most farms do not have sufficient water supply to permit high rates of water exchange. Boyd (1990) suggested that it might be possible in some locations to partially drain and quickly refill ponds with well water of low ammonia concentration when ammonia-nitrogen concentrations become too high. This combination of nightly aeration with partial water exchange might be the best method for eliminating low nighttime DO concentrations and high concentrations of total ammonia, thereby increasing production in ponds with high feeding rates.

The quantities of total suspended solids were much greater in aerated ponds than in non-aerated ponds, while the total volatile solids values were similar. The aeration-induced mud turbidity interfered with algal growth in the aerated ponds, and thus reduced the availability of natural foods for open-pond tilapia. Lowered primary productivity in aerated ponds may also cause significantly higher concentrations of total ammonia (Teichert-Coddington and Green, 1993), which further reduces growth of open-pond tilapia. A combination of all of these factors probably caused the significantly lower growth rates of open-pond tilapia in the aerated ponds. Teichert-Coddington and Green (1993) demonstrated that aeration could enhance yields but that it had little effect on water quality other than to increase turbidity. Thus, another method to increase nighttime DO levels may be to circulate water. Water circulation appears to stimulate phytoplankton growth (Sanares et al., 1986) which could increase DO production by photosynthesis (Boyd, 1990).

Anticipated Benefits

This study demonstrated the feasibility of the tilapia-tilapia cage-cum pond integrated culture system which entails the intensive cage culture of large tilapia in earthen ponds in which small tilapia are semi-intensively cultured. Results also indicated that nighttime aeration for five hours improved growth performance of caged tilapia stocked at the highest biomass for use in the integrated culture system. This culture system will allow small-scale farmers to maximize their profits. Since open-pond tilapia effectively recovered wastes, this culture system benefits both aquaculture production and the environments receiving pond water discharge.

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Management to Minimize the Environmental Impacts of Pond Draining

Eighth Work Plan, Thailand Research 3 (TR3)

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Introduction

Nutrient enrichment of pond waters is an essential management practice in aquaculture (Pillay, 1990; Boyd, 1990). However, the discharge of nutrient-rich water, an environmental regulatory concern in many countries, may result in the deteriorated quality of receiving waters (Pillay, 1992). Means to minimize the environmental impacts of pond effluents include minimizing the use of nutrients, managing drainage to retain most nutrients in the pond system, and maximizing the use of surplus materials in sediments by fish during grow-out. Several of these topics are the subject of current CRSP research. Previous research in Thailand has indicated that the most efficient nutrient application systems include combined organic and inorganic materials (Knud-Hansen et al., 1993). Such inputs result in the production of approximately 4,800 kg ha^{-1} of Nile tilapia (*Oreochromis niloticus*) per 150-day grow-out (Diana et al., 1994). Moreover, supplemental feeding of tilapia, combined with fertilization, increases fish yield and the mean harvest size of fish. When fish reach 100 to 150 g supplementation of 50% satiation feeding, in addition to optimal fertilization, appears to be the most efficient system for growing large tilapia (Diana et al., 1996).

Nutrient analyses of source and pond waters in Thailand indicate that fertilization systems optimal for fish growth cause a minimal increase in concentrations of phosphorus (P) and nitrogen (N) in pond waters during the course of grow-out (Diana et al., 1994). While nutrients may be lost with overflow water, they do not load receiving waters beyond normal levels during rain events. However, the water quality of effluents discharged during draining at harvest may be considerably lower, due to the accumulation of materials in pond sediments or in pond water near the soil-water interface (Pillay, 1992).

In this study we assess several harvest strategies to:

1. evaluate the amount of N, P, and solids discharged from pond waters during harvest draining; and
2. identify fish harvest techniques that may reduce the loading of nutrients and solids in effluent waters.

Methods and Materials

Fifteen earthen ponds, 200 m^2 in surface area, with an average depth of 1.2 m were used to culture sex-reversed Nile tilapia at the Asian Institute of Technology, Thailand. All ponds were fertilized weekly with 1.2 kg urea (28 kg N ha^{-1}) and 0.7 kg triple superphosphate (TSP) (7 kg P ha^{-1}), increasing TSP application to 1.4 kg (14 kg P ha^{-1}) from week 9 through 17. On 25 February 1997 fish were stocked at 1.5 fish m^{-2} at a size of 103 ± 1 g (mean ± SE). Fish were fed with commercial floating feed (30% crude protein) at 50% satiation six days per week. Satiation feeding rates were determined for each pond by measuring the total amount of feed consumed during two feeding session from 1000 to 1100 h and from 1400 to 1500 h on the Wednesday of each week. The 50% satiation feeding rate was based on the mean satiation feeding rate of 15 ponds. This rate was applied to each pond from Thursday through Tuesday. Fish were cultured 113 to 119 days and then harvested from June 19-25. Tilapia reproduction occurred in all ponds.

Pond water column samples, taken biweekly at 0900 h, were analyzed for total alkalinity, total ammonium-nitrogen, nitrite-nitrogen, nitrate-nitrite-nitrogen, total nitrogen, soluble reactive phosphorus, total phosphorus, organic carbon, chlorophyll *a*, total suspended solids, and total volatile solids using standard methods (APHA, 1980; Egna et al., 1987). Temperature, dissolved oxygen, pH (at 20 cm below the surface), and Secchi disk depth were also measured *in situ* according to the same schedule. In addition, monthly diel temperature, dissolved oxygen, pH, alkalinity, and total ammonium-nitrogen were determined at 0600, 0900, 1400, 1600, 1800, 2300, and 0600 h in each pond.

The experiment incorporated five management procedures that tested three harvest techniques. The management procedures were as follows: (A) fish were partially anaesthetized by addition of tea seed cake (10 ppm), 1.5 h prior to harvest. The pond was then seine-netted three times—an operation involving four persons; (B) ponds were limed (75 ppm calcium hydroxide) 24 hours prior to harvest, completely drained, and then fish were collected from a harvesting pit; (C) ponds were completely drained and fish collected from a harvesting pit; (D) ponds were drawn down to 50 cm and fish harvested by two seinings, followed by complete draining and collection of the remaining fish from a harvesting pit; and (E) involved the same draining and harvesting technique as in treatment D, but the pond water was drained into the empty ponds of procedure D. Each procedure/treatment was replicated three times in a blocked design. The locations of treatments within blocks were assigned on a random basis, with the exception that ponds under treatments D and E had to be adjacent to facilitate drainage of water from ponds in treatment E to ponds in treatment D.

The appropriate tea seed cake concentration (10 ppm) that was used to anesthetize the fish in treatment A was determined using a preliminary toxicity test that exposes tilapia (mean weight 500 g) to a series of tea seed cake concentrations over a 3-hour period. To establish the harvest efficiency of ponds in this treatment, ponds received a lethal dose of tea seed cake (15 ppm) one week post harvest. Pond water and tilapia fingerlings (5-10 g size) were tested for toxicity one week after harvest and found to be safe.

Similarly, a preliminary experiment on lime flocculation of suspended solids determined the liming dose used in treatment B.

Complete draining of pond water in treatments B and C was achieved by sequential draining. Ponds were first drained to 50 cm, then to 25 cm, and finally to 0 cm by lowering the pump to the respective water depths. The fish were then harvested from a harvesting pit. The draining and harvest technique described for treatments D and E is commonly practiced in Thailand; the pump was placed at the bottom of the pond.

Sediment deposition on the pond bottom was measured for ponds of treatments B and C; these ponds were completely drained, without seining. To measure pond mud deposition, bamboo sticks marked with a scale were inserted at three representative points in each pond at the beginning of the experiment. Sediment level increases in reference to previous marks were measured once ponds were completely drained at the end of experiment.

Pond water column samples were collected from treatment A and effluent samples, taken during harvest draining from treatments B, C, D, and E were collected when pond water levels were 100-50 cm, 50-25 cm, and 25-0 cm. For each treatment three effluent samples were collected for each water level, and mixed to provide a single representative sample for each depth. Column water samples of treatment A and effluent samples of treatments B, C, D, and E were analyzed for total N, total P, total solids, total volatile solids, suspended solids, volatile suspended solids, settleable matter, and five-day biochemical oxygen demand (BOD_5).

Data were analyzed using the Statgraphic 7.0 statistical package. Fish growth (g d^{-1}), survival (%), net yield (kg ha^{-1} d^{-1}) and extrapolated yield (kg ha^{-1} yr^{-1}) were calculated for each pond. Food conversion ratio (FCR) was calculated as the feed applied over the entire experiment divided by the net yield of each pond. Means include standard error, and differences were considered significant at an alpha level of 0.05 unless otherwise stated.

Table 1. Stocking and harvest size, fish growth, survival, food conversion ratio, and production of Nile tilapia cultured in fertilized ponds and supplemented with 50% satiation feeding.

Pond	Mean Stocking Size (g)	Mean Harvest Size (g)	Mean Growth (g d^{-1})	Survival (%)	Food Conversion Ratio	Net Fish Yield (kg ha^{-1} d^{-1})	Extrapolated Yield (kg ha^{-1} yr^{-1})
1	101	539	3.8	90	1.4	50.8	18554
2	101	565	4.1	100	1.2	61.6	22481
3	102	551	3.8	97	1.4	54.8	19998
4	102	540	3.7	100	1.3	56.2	20512
5	106	493	3.3	99	1.5	48.6	17724
6	106	518	3.5	95	1.5	48.7	17759
7	106	509	3.5	96	1.5	50.5	18426
8	111	529	3.7	96	1.4	53.0	19332
9	103	541	3.7	90	1.4	49.0	17876
10	101	543	3.8	98	1.3	55.3	20169
11	103	448	2.9	99	1.6	42.7	15597
12	100	514	3.6	97	1.4	52.6	19211
13	99	581	4.1	96	1.2	58.7	21432
14	105	528	3.6	93	1.5	49.3	17987
15	98	522	3.7	100	1.3	56.2	20527
Mean ± SE	103 ± 1	528 ± 8	3.7 ± 0.1	97 ± 1	1.4 ± 0.03	52.5 ± 1.2	19173 ± 449

Results

Mean values for harvest size, growth, survival, food conversion ratio, net yield and extrapolated yield of tilapia obtained from each pond (culture period of 113 to 119 days) are shown in Table 1. The mean satiation feeding level for tilapia, calculated weekly, ranged from 43.04 ± 1.4 to 165.3 ± 7.1 kg ha^{-1} d^{-1}, over the course of the experiment. The actual amount of feed applied to each pond at the rate of 50% mean satiation ranged from 21.5 kg ha^{-1} d^{-1} during the initial week to 82.5 kg ha^{-1} d^{-1} during the final weeks of the trials (Figure 1). Based on the satiation feeding level and fish biomass in each pond at stocking and harvest, mean satiation feeding rates were $2.8 \pm 0.1\%$ BWD for the initial week and $2.0 \pm 0.1\%$ BWD for the final week with actual feeding rates of 1.4% BWD for the initial week and 1.0% BWD during the final week of the experiment. The final week feeding rate decreased to 0.9% BWD when the weights of tilapia fry produced in ponds were taken into account.

Table 2 presents a summary of the physico-chemical parameters of pond waters measured at biweekly intervals at 0900 h. Similarly, the mean monthly diel temperature, dissolved oxygen, pH, alkalinity, and total ammonium-nitrogen recorded over a 24-hour period at 0600, 0900, 1400, 1600, 1800, 2300, and 0600 h are shown in Table 3.

The efficiencies of three different harvest techniques used during this experiment are given in Table 4. Efficiencies are expressed as the number of fish captured as a percentage of all surviving fish at the time of harvest.

Sediment deposition ranged from 3.6 to 10.2 cm with a mean of 6.3 ± 1.0 cm (Table 5). Sediment deposition varied slightly between three locations within a pond—the base of the dike slope, the center of the pond bottom and half-way between these points.

Water quality data from column water samples in treatment A and effluent water samples from treatments B, C, D, and E are presented in Table 6. Values for all parameters, except total nitrogen (BOD_5, settleable matter total solids, total volatile solids, total suspended solids, volatile suspended

Table 2. Mean and range values for physico-chemical parameters of pond water measured biweekly at 0900 h over the experimental period.

Physico-Chemical Parameters	Mean ± SE	Range
Temperature (°C)	30.2 ± 0.0	30.0 - 30.6
Dissolved Oxygen (mg l^{-1})	3.1 ± 0.1	2.2 - 3.8
pH	6.9	6.5 - 7.7
Secchi Disk Visibility (cm)	19 ± 1	10 - 29
Alkalinity (mg l^{-1} $CaCO_3$)	86.8 ± 8.9	31.1 - 154.4
Total Ammonium-Nitrogen (mg l^{-1})	3.81 ± 0.59	0.82 - 8.25
Nitrite-Nitrogen (mg l^{-1})	0.28 ± 0.03	0.15 - 0.53
Nitrate- and Nitrite-Nitrogen (mg l^{-1})	1.10 ± 0.14	0.42 - 2.04
Total Nitrogen (mg l^{-1})	6.61 ± 0.43	4.62 - 9.44
Soluble Reactive Phosphorus (mg l^{-1})	0.11 ± 0.05	0.01 - 0.69
Total Phosphorus (mg l^{-1})	0.53 ± 0.06	0.27 - 1.20
Organic Carbon (mg l^{-1})	93.2 ± 2.9	76.7 - 120.4
Chlorophyll *a* (μg l^{-1})	132 ± 15	62 - 226
Total Suspended Solids (mg l^{-1})	113.5 ± 11.5	63.0 - 219.5
Volatile Suspended Solids (mg l^{-1})	30.8 ± 1.7	19.5 - 48.8
Pond Water Depth (m)	1.16 ± 0.02	1.05 - 1.33

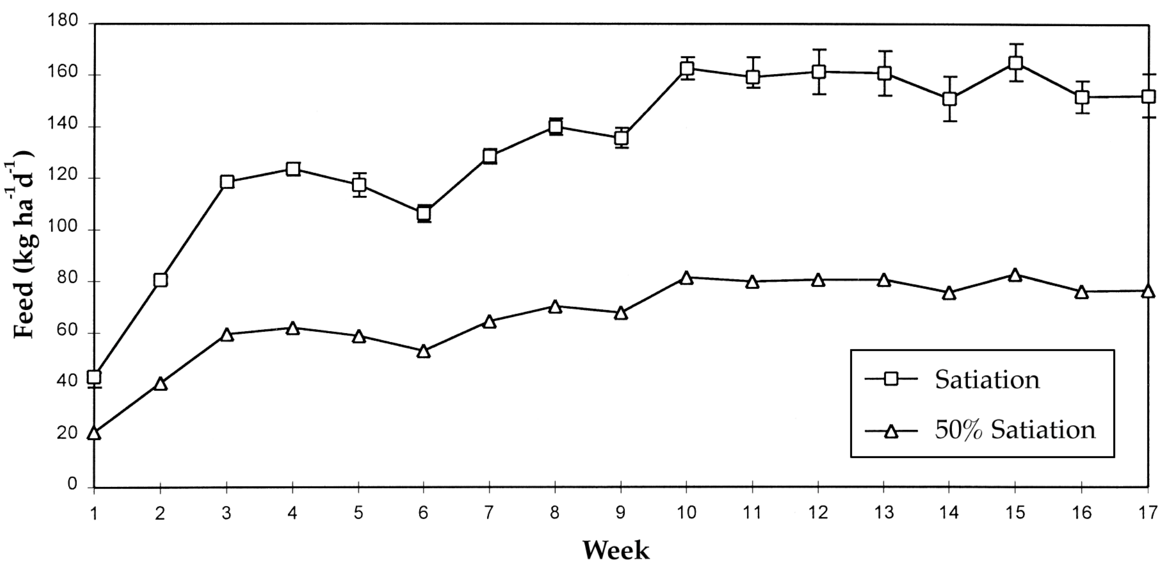

Figure 1. Mean satiation feeding level (kg ha^{-1} d^{-1}) (n = 15 ponds) and mean feeding rate (50% of mean satiation level) applied to each pond. Mean stocking size of fish was 103 ± 1 g at a stocking density of 1.5 fish m^{-2}. Mean harvest size of fish was 528 ± 8 g.

solids, and total phosphorus), were greater in effluent waters, for all harvest techniques, than they were in water column samples (of treatment A). Values for effluent water parameters increased significantly as pond water level was lowered during draining. Effluent values were also greatly increased after seining, in treatment D. Liming (treatment B) reduced the concentration of total suspended solids and phosphorus in the water column from the surface to 25 cm depth. However, the concentrations of solids and nutrients were substantially greater in the bottom water (0-25 cm).

Table 3. Mean monthly diel profile of water quality parameters over the experimental period.

Parameters	0600 h	0900 h	1400 h	1600 h	1800 h	2300 h	0600 h
Temperature (°C)	29.8 ± 0.1	30.0 ± 0.0	31.6 ± 0.1	32.0 ± 0.1	31.5 ± 0.2	30.5 ± 0.0	29.4 ± 0.1
Dissolved Oxygen (mg l^{-1})	0.3 ± 0.0	1.6 ± 0.1	5.1 ± 0.3	6.4 ± 0.4	6.4 ± 04	1.8 ± 0.2	0.3 ± 0.0
pH	6.8	6.9	7.0	7.1	7.2	6.8	7.1
Alkalinity (mg l^{-1} $CaCO_3$)		91.1 ± 9.0		88.7 ± 8.9			94.6 ± 9.2
Total Ammonium Nitrogen (mg l^{-1})		3.1 ± 0.5		2.8 ± 0.5			3.4 ± 0.5

Table 4. Efficiency of three harvest techniques. 1. Seining undrained pond after application of tea seed cake (treatment A); 2. Drainage of pond and collection of fish in a harvesting pit (treatments B and C); 3. Partial drainage of pond, followed by seining, then complete drainage of pond and collection of the remaining fish in a harvesting pit (treatments D and E).

Activity	Harvest Technique		
	1 (n = 3) *	2 (n = 6)	3 (n = 6)
Stocked (fish $pond^{-1}$)	300	300	300
1st Seining (%)	76 ± 5		66 ± 1
2nd Seining (%)	15 ± 4		19 ± 2
3rd Seining (%)	6 ± 1		
Collection from Harvest Pit (%)		100	15 ± 2
Harvest (fish $pond^{-1}$)	282 ± 4	290 ± 4	288 ± 4
Survival (fish $pond^{-1}$)	291 ± 3	290 ± 4	288 ± 5
Harvest Efficiency (%)	97 ± 3	100	100

* The number of fish not collected during seining was determined by the application of a lethal dose of tea seed cake (15 ppm) to ponds.

Table 5. Pond sediment deposition over the course of the experimental period.

Pond #	Sediment Deposition (cm)			
	Base of dike slope	*Midway between base of slope and pond center*	*Pond center*	*Mean*
1	1.5	6.1	3.3	3.6
2	5.5	5.5	6.5	5.8
7	5.5	7.0	7.6	6.7
8	6.3	4.7	2.0	4.3
12	6.9	6.7	8.6	7.4
15	10.5	11.5	8.5	10.2
Mean ± SE	6.0 ± 1.2	6.9 ± 1.1	6.1 ± 1.1	6.3 ± 1.0

Table 6. Comparison of water quality of column water samples from undrained ponds (A) and effluent quality during draining (B, C, D, and E). A = Harvesting fish by three seinings, without pond draining, after anaesthetizing fish using tea seed cake (n = 3). B = Complete draining of pond water after liming and fish harvested from harvest pit (n = 3). C = Complete draining of pond water and fish harvested from harvesting pit (n = 3). D and E = Draw down of water to 50 cm and fish harvested by two seinings and followed by complete draining and fish collection from harvesting pit (n = 6).

Effluent Parameter	Treatment	Pond Water Level During Draining			Weighted Mean	Probability
		100-50 cm	*50-25 cm*	*25-0 cm*		
Biological	A*	n/a	n/a	n/a	31 ± 4	Harvest
Oxygen	B	57 ± 7	56 ± 5	228 ± 27	100 ± 4	Technique
Demand	C	51 ± 10	47 ± 13	87 ± 22	59 ± 13	$P > 0.05$
(BOD_5)	D + E	63 ± 21	167 ± 46	149 ± 33	111 ± 27	Depth Level
(mg l^{-1})	Mean ± SE	59 ± 10	109 ± 28	153 ± 23		$P < 0.05$
Settleable	A*	n/a	n/a	n/a	0.0 ± .0	Harvest
matter	B	0.1 ± 0.0	0.2 ± 0.1	37.0 ± 10.0	9.3 ± 2.5	Technique
(ml l^{-1})	C	0.2 ± 0.1	0.3 ± .1	10.7 ± 6.8	2.9 ± 1.7	$0.1 > P > 0.05$
	D + E	3.2 ± 1.1	28.1 ± 12.9	22.0 ± 4.8	14.2 ± 4.0	Depth Level
	Mean ± SE	1.7 ± 0.7	14.2 ± 7.4	22.9 ± 4.5		
						$P < 0.05$
Total	A*	n/a	n/a	n/a	842 ± 65	Harvest
Solids	B	1013 ± 17	1132 ± 38	5978 ± 1347	2284 ± 322	Technique
(mg l^{-1})	C	1053 ± 29	1058 ± 80	3575 ± 1251	1685 ± 345	$0.1 > P > 0.05$
	D + E	1589 ± 187	5937 ± 2234	4536 ± 564	3413 ± 686	Depth Level
	Mean ± SE	1311 ± 123	3516 ± 1291	4656 ± 541		
						$P < 0.05$
Total	A*	n/a	n/a	n/a	124 ± 23	Harvest
Volatile	B	163 ± 14	159 ± 16	692 ± 128	295 ± 27	Technique
Solids	C	150 ± 20	149 ± 20	382 ± 123	208 ± 43	$P < 0.05$
(mg l^{-1})	D + E	190 ± 16	589 ± 165	549 ± 62	380 ± 42	Depth Level
	Mean ± SE	173 ± 11	371 ± 103	543 ± 58		$P < 0.05$
Total	A*	n/a	n/a	n/a	205 ± 50	Harvest
Suspended	B	119 ± 10	178 ± 33	5682 ± 1480	1525 ± 361	Technique
Solids	C	276 ± 22	274 ± 50	1957 ± 691	696 ± 186	$0.1 > P > 0.05$
(mg l^{-1})	D + E	749 ± 201	5180 ± 2320	3913 ± 632	2648 ± 729	Depth Level
	Mean ± SE	473 ± 128	2703 ± 1335	3866 ± 608		$P < 0.05$
Volatile	A*	n/a	n/a	n/a	52 ± 11	Harvest
Suspended	B	39 ± 10	48 ± 8	577 ± 130	176 ± 26	Technique
Solids	C	53 ± 8	49 ± 13	223 ± 65	94 ± 21	$P < 0.05$
(mg l^{-1})	D + E	100 ± 12	502 ± 174	408 ± 50	278 ± 51	Depth Level
	Mean ± SE	73 ± 10	275 ± 107	404 ± 54		$P < 0.05$
Total	A*	n/a	n/a	n/a	13.9 ± 3.4	Harvest
Nitrogen	B	10.1 ± 1.7	15.3 ± 2.4	20.3 ± 3.4	13.± 1.6	Technique
(mg l^{-1})	C	4.9 ± 0.4	5.1 ± 0.7	8.5 ± 0.7	5.9 ± .2	$P < 0.05$
	D + E	6.6 ± 0.7	11.6 ± 2.0	12.2 ± 0.9	9.3 ± 0.8	Depth Level
	Mean ± SE	7.1 ± 0.7	10.9 ± 1.5	13.3 ± 1.6		$P < 0.05$
Total	A*	n/a	n/a	n/a	0.97 ± 0.24	Harvest
Phosphorus	B	0.58 ± 0.10	0.63 ± 0.08	2.23 ± 0.26	1.01 ± 0.03	Technique
(mg l^{-1})	C	0.88 ± 0.21	0.87 ± 0.21	1.53 ± 0.06	1.04 ± 0.15	$P > 0.05$
	D + E	0.80 ± 0.09	0.95 ± 0.12	1.24 ± 0.16	0.95 ± 0.10	Depth Level
	Mean ± SE	0.76 ± 0.07	0.85 ± 0.09	1.56 ± 0.16		$P < 0.05$

* Column water sample of ponds which were not drained and fish were harvested only by seining.

Discussion

The growth of tilapia in the current experiment averaged 3.7 g d^{-1}. Tilapia grew from 103 to 528 g over a mean culture period of 116 days, giving a mean yield of 52.5 kg ha^{-1} d^{-1}. This growth is comparable to, or higher than, that achieved in other studies (Green, 1992; Diana et al., 1994; Diana et al., 1996). This suggests that the feeding (daily feeds of 1.4% BWD dropping to 1% BWD), fertilization (urea at 28 kg N ha^{-1} and TSP at 7 kg P ha^{-1}, increasing to 14 kg P ha^{-1}, weekly), and stocking (1.5 fish m^{-1}) regimes utilized during the course of this experiment were sufficient to ensure good growth rates.

Mean total ammonium-nitrogen concentrations increased constantly after the fifth week of the experiment; however, the increase did not cause fish mortality. Perhaps this is because of continually low pH values, that did not exceed 7.7 (see Table 2) possibly suggesting that to further improve the feeding system nitrogen fertilization can be reduced.

The commonly used Thai practice of partially draining a pond, seining, then completely draining to collect the remaining fish (as incorporated in treatments D and E) results in a large amount of waste being discharged. The wastes discharged from a one-hectare pond would be equivalent to 1.1 t of BOD_5, 142 m^3 of settleable matter, 34.1 t of total solids, 3.8 t of total volatile solids, 26.5 t of total suspended solids, 2.8 t of volatile suspended solids, 93 kg of total nitrogen and 9.5 kg of total phosphorus. Adoption of the technique of complete drainage, to allow collection of fish (as used in treatment C) results in the following reductions of effluent levels: 47% of BOD_5, 80% of settleable matter, 51% of total solids, 45% of total volatile solids, 74% of total suspended solids, 68% of volatile suspended solids and 37% of total nitrogen.

The water quality of pond effluent in the limed treatment (B) indicates that liming concentrates pollutants in the pond bottom waters. Hence, if ponds are limed, then careful treatment of bottom water during drainage disposal should be considered.

It is possible to use fish culture ponds, without draining them, for several years because natural microbial and physico-chemical processes remove nutrients and organic matter from pond water (Tucker et al., 1990). For example, in the southeast United States channel catfish (*Ictalurus punctatus*) are cultured in ponds which are not drained for as long as 20 years. In spite of large inputs of metabolic waste, resulting from feeding practices, nutrients and organic matter in the water column do not reach deleterious levels (Hollerman and Boyd, 1985; Seok et al., 1995). The present study shows that the use of tea seed cake to anesthetize tilapia can allow effective harvest by seining, without draining the pond. Harvest efficiency of 97% was achieved using this technique. Alternatively, the discharge of drainage water into the environment can be reduced by using drained water to refill empty ponds, as in treatment E. However, accumulation of sediment will necessitate eventual drainage of culture ponds. Deposition of sediments occurred at a rate of 6.3 ± 1.0 cm over the four months of the grow-out period. To minimize the discharge of waste products, and to avoid excessive accumulation of sediment we propose that ponds be drained every four or five years.

Anticipated Benefits

This study has evaluated the content and quantity of tilapia pond effluent of harvest draining and demonstrated the potential for tilapia harvest that do not involve draining. Results of the study have shown that modified harvest draining techniques reduce the amount of waste discharged. Implementation of the techniques suggested in this study will greatly minimize the environmental impacts of pond draining.

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A Bioenergetics Growth Model for Nile tilapia (*Oreochromis niloticus*) based on Limiting Nutrients and Fish Standing Crop in Fertilized Ponds

Thailand Special Topics Research 1

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Introduction

Aquaculture ponds are complex ecosystems. Computer modeling is a valuable tool for the analysis of complex systems (Cuenco, 1989) and is becoming an important component of research efforts that are directed toward improving our understanding of aquaculture pond ecosystems and developing management practices that optimize resource utilization (Piedrahita, 1988).

Nile tilapia (*Oreochromis niloticus*) is one of the most popular species cultured in many tropical countries (including Thailand). Nile tilapia are commonly grown in semi-intensive culture using fertilization to increase primary production that is used by tilapia for food (Boyd, 1976; Diana et al., 1991). A significant increase in fish yield following the successful addition of fertilizers is generally due to the growth of algae and the subsequent transformation of algae to fish flesh through food webs of ponds (McNabb et al., 1990). Nitrogen, phosphorus, and carbon are three important nutrients required for algal growth. The C:N:P ratio for algae is approximately 40:7:1 by weight (Round, 1973; Vallentyne, 1974; Wetzel, 1983). There is considerable inconsistency in algal yields obtained from ponds receiving the same inputs of nitrogen and/or phosphorus fertilizers (McNabb et al., 1990). A shortage of dissolved inorganic carbon may be one cause of inconsistent yields (McNabb et al., 1988). Therefore, it is essential to identify which of these three nutrients is a limiting factor for primary production when estimating the amount of natural foods available to fish growth.

Various growth models have been developed for Nile tilapia (Liu and Chang, 1992; Nath et al., 1993; Bolte et al., 1995); however, none of them have linked a limiting nutrient with Nile tilapia growth. Liu and Chang (1992) modeled the parameter of relative feeding level (f) using a fertilizer richness parameter to estimate the available food resources parameter in Ivlev's equation (1961). They assumed this fertilizer richness parameter would correspond to the amount of chicken manure added to the ponds. However, manure input rates cannot be easily extended for use in ponds that receive various levels of fertilizer inputs or a mixture of organic and synthetic fertilizers, because an estimate of the fertilizer richness parameter would be required (Bolte et al., 1995). Moreover, Ivlev (1961) assumed that natural food availability was a function of the number of fish instead of fish standing crop as suggested by Hepher (1978). It is more accurate to estimate f as a function of fish standing crop and potential net primary productivity derived by a limiting nutrient rather than fish number and total fertilizer input.

The purpose of this study was: 1) to develop a bioenergetics growth model for Nile tilapia cultured in fertilized ponds through the synthesis of currently available information on fish physiology and pond dynamics; and 2) to use the model to evaluate the effects of different factors (body size, temperature, dissolved oxygen (DO), unionized ammonia (UIA), and food availability) on Nile tilapia growth in fertilized ponds.

The Models

Model Development

The model was written using a dynamic modeling language called STELLA® II (High Performance Systems, Inc., 1990) and was based on a model developed by Ursin (1967). The model used a time step of one day, and the equations were solved using a 4th-order Runge-Kutta numerical integration method.

Ursin (1967) indicated that anabolism and catabolism may have different exponents in relation to fish weight (with subsequent effects on fish growth) and expressed the rate of change of fish body weight as the difference between anabolism and catabolism:

$$dW/dt = H\,W^m - k\,W^n \qquad (1)$$

where

W = fish weight (g),

t = time (day),

H = coefficient of net anabolism ($g^{1-m}\,d^{-1}$),

m = exponent of body weight for net anabolism,

k = coefficient of fasting catabolism ($g^{1-n}\,d^{-1}$),

n = exponent of body weight for fasting catabolism.

Because gross catabolism comprises feeding and fasting catabolism (Ursin, 1967), equation 1 can be re-written as:

$$dW/dt = b\,dR/dt - (a\,b\,dR/dt + K\,W^n) \qquad (2)$$

where

dR/dt = daily ration ($g\,d^{-1}$),

b = efficiency of food assimilation (dimensionless),

a = fraction of the food assimilated that is used for feeding catabolism (dimensionless).

The terms, $b\,dR/dt - (a\,b\,dR/dt + K\,W^n)$, on the right hand of equation 2 represent gross anabolism, feeding catabolism and fasting catabolism, respectively. From an energetic point of view, the parameter b refers to the proportion of the gross energy or food intake that is available as metabolizable energy (Nath et al., 1993) and is typically not constant but decreases with increasing food availability for most fish, including tilapias (Caulton, 1982). The parameter a accounts for further losses of metabolizable energy via heat increment and urinary excretion (Nath et al., 1993). Thus, gross energy available for metabolism is represented by $b\,dR/dt$ on the right hand side of equation 2, whereas the second and third terms, $a\,b\,dR/dt$ and $K\,W^n$, represent feeding and maintenance requirements.

Fish growth is influenced not only by intrinsic factors such as fish size but also by a variety of environmental factors (Brett, 1979), including water temperature (Brett et al., 1969; Elliott, 1976), photoperiod (Gross et al., 1965), dissolved oxygen (Stewart et al., 1967; Doudoroff and Shumway, 1970), unionized ammonia concentrations (Colt and Tchobanoglous, 1978) and food availability (Brett, 1971). These factors affect fish growth via their impacts on food consumption (Brett, 1979; Cuenco et al., 1985). Due to the warm climate and shallowness of most tropical fish ponds, temperature and photoperiod are not likely to be limiting for food consumption.

Cuenco et al. (1985) reported that food consumption was not affected when DO was above a critical limit (DO_{crit}); DO_{crit} decreased more or less linearly with decreasing DO levels until a minimum level (DO_{min}) was reached, below which fish would not feed. The function (δ) describing the effects of DO on food consumption would be expressed as:

$$\delta = 1.0 \qquad \text{if } DO > DO_{crit} \qquad (3a)$$

$$\delta = (DO - DO)/(DO_{crit} - DO_{min}) \qquad \text{if } DO_{min} \le DO \le DO_{crit} \qquad (3b)$$

$$\delta = 0.0 \qquad \text{if } DO < DO_{min} \qquad (3c)$$

Colt and Armstrong (1981) and Cuenco et al. (1985) indicated that food consumption was not affected when UIA was below a critical limit (UIA_{crit}) and food was not consumed when UIA reached a maximum level (UIA_{max}), between which food consumption decreased with increasing UIA. The function (υ) describing the effects of UIA on food consumption could be expressed as follows:

$$\upsilon = 1.0 \qquad \text{if } UIA < UIA_{crit} \qquad (4a)$$

$$\upsilon = (UIA_{max} - UIA)/(UIA_{max} - UIA_{crit}) \qquad \text{if } UIA_{crit} \le UIA \le UIA_{max}) \qquad (4b)$$

$$\upsilon = 0.0 \qquad \text{if } UIA > UIA_{max} \qquad (4c)$$

The quantity of natural food consumed by tilapia, based on modeling rations proposed by Ursin (1967), is expressed as:

$$dR/dt = d\,\upsilon\,h\,f\,W^m \qquad (5)$$

where

- h = coefficient of food consumption (g^{1-m} d^{-1}) and
- f = relative feeding level ($0 < f < 1$, dimensionless).

To link the relative feeding level with potential net primary productivity (PNPP) and standing crop of Nile tilapia, Ivlev's (1961) equation can be modified as following:

$$f = r/R = 1 - \exp(-s\,P/B) \qquad (6)$$

where

- r = actual daily ration (g d^{-1}),
- R = maximal daily ration (g d^{-1}),
- s = coefficient of food proportionality (dimensionless),
- P = PNPP (g C m^{-3} d^{-1}), and
- B = standing crop of Nile tilapia (g m^{-3}).

However, Ivlev (1961) initially defined P as concentration of natural food and B as the number of fish.

PNPP used to estimate the quantity of natural food in ponds is the minimal PNPP (P_c, P_n, and P_p) derived from total dissolved inorganic carbon (DIC), total dissolved inorganic nitrogen (DIN) and total dissolved inorganic phosphorus (DIP), respectively (see equation 7).

$$P = \mathrm{Min}\,(P_c, P_n, P_p) \qquad (7)$$

The following equations for calculating P_c, P_n, and P_p are based on Lannan (1993):

$$P_c = 12\lambda\,(A/50)\,\{[(H^+)^2/k_1 + H^+ + k_2]/(H^+ + 2k_2)\} \qquad (8)$$

$$k_1 = (T/15 + 2.6)\,10^{-7} \qquad (8a)$$

$$k_2 = (T/10 + 2.2)\,10^{-11} \qquad (8b)$$

where

- P_c = PNPP derived from DIC (g C m^{-3} d^{-1}),
- λ = efficiency of carbon fixation (dimensionless),
- A = alkalinity (mg $CaCO_3$ l^{-1}),
- H^+ = hydrogen ion concentration (moles l^{-1}),
- k_1 = the first dissociation constant for carbonate/bicarbonate system,
- k_2 = the second dissociation constant for carbonate/bicarbonate system,
- T = water temperature (°C).

The constants of 12 and 50 in equation 10 are gram equivalent weights of C and $CaCO_3$.

In equations 9 and 10, it is assumed that there is no threshold concentration of DIN or DIP below which the respective nutrients are not available for photosynthesis even though observations by Hepher (cited by Boyd, 1979) suggest that such thresholds may exist. However, until definitive information is available, the simplifying assumption that all the DIN and DIP are available seems reasonable (Lannan, 1993).

$$P_n = 40\,D_n/7 \qquad (9)$$

$$P_p = 40\,D_p \qquad (10)$$

where

- P_n = PNPP derived from DIN (g C m^{-3} d^{-1}),
- D_n = DIN (mg N l^{-1}),
- P_p = PNPP derived from DIP (g C m^{-3} d^{-1}),
- D_p = DIP (mg P l^{-1}).

The constants of 40 and 7 were based on carbon:nitrogen:phosphorus ratios of 40:7:1 by weight (Round, 1973; Vallentyne, 1974; Wetzel, 1983).

Finally, the growth rates (dW/dt) of Nile tilapia can be expressed as follows:

$$dW/dt = \{b\,(1 - a)\,\delta\,\upsilon\,h\,[1 - \exp(-s\,P/B)]\,W^m\} - k\,W^n \qquad (11)$$

Ursin (1967) and Sperber et al. (1977) assumed that the coefficient of catabolism (k) increases exponentially with temperature. Nath et al. (1993) modified this exponential form to include the minimum temperature below which the fish species can not survive (T_{min}) as follows:

$$k = k_{min} \exp [j (T - T_{min})] \qquad (12)$$

where

k_{min} = coefficient of fasting catabolism ($g^{1-m}d^{-1}$) at T_{min} and

j = constant to describe temperature effects on catabolism (1/°C).

Parameter Estimations

Nath et al. (1993) analyzed oxygen consumption data for fasting Nile tilapia and estimated the mean for n to be 0.81, but they retained $n = 1$ in their growth model because insertion of $n = 0.81$ during their test runs of the model resulted in growth rates for tilapia far in excess of observed rates. This finding was consistent with the results of Liu and Chang (1992); however, in the present model $n = 0.81$ and $m = 0.67$ (approximated by Ursin, 1967) were used.

I assumed the efficiency of food assimilation (b) to be 0.62 (Nath et al., 1993), which was the mean value of the range of assimilation efficiencies (0.53-0.70) for Nile tilapia reported by Meyer-Burgdorff et al. (1989). The parameter b was assumed to be constant in this model, although it was found to decrease with increased food intake (Meyer-Burgdorff et al., 1989) and to be influenced by other factors such as temperature (Caulton, 1982). The values of parameters a and h were assumed to be 0.53 (Nath et al., 1993) and 0.8 (Bolte et al., 1994) in this model, respectively, for Nile tilapia feeding on natural foods in fertilized ponds.

Based on laboratory experiments with Nile tilapia (Gannam and Phillips, 1993), T_{min} appears to be about 15°C. Nath et al. (1993) used data on fasting Nile tilapia from Satoh et al. (1984), who estimated k_{min} and j to be 0.00133 and 0.0132, respectively. These estimations were also used in this model.

Nile tilapia can tolerate low DO and survive environments where other fish species can not exist (except air breathing species) (Boyd, 1990) due to its ability to use atmospheric oxygen when DO concentration drops to less than 1 mg l^{-1} (Chervinski, 1982). The lowest tolerance limit of DO reported for Nile tilapia ranges from 0.1 to 0.3 mg l^{-1} under different environmental conditions (Ahmed and Magid, 1968; Magid and Babiker, 1975). However, DO_{crit} and DO_{min} have not been well defined. Teichert-Coddington and Green (1993) reported that a practical threshold DO for Nile tilapia was not greater than 10% of saturation. Therefore, DO_{crit} and DO_{min} used in the present model were 1.0 and 0.3 mg l^{-1}, respectively. Abdalla (1989) determined that $UIA_{max} = 1.40$ mg l^{-1} and $UIA_{crit} = 0.06$ mg l^{-1} for Nile tilapia.

To estimate coefficient of food proportionality (s), data from three fertilized ponds (Diana et al., 1994) were used. The experiment was conducted for 162 days at the Ayutthaya Freshwater Fisheries Station located at Bang Sai, Thailand. Using the above equations, the estimated mean value of s was 17.31 ± 1.25.

Data Requirement for Model Validation

Almost all values of parameters used in the model were derived from the literature. To test the validity of the model, simulated outputs were compared with independently obtained experimental results that were not used during the process of model development. The following two sets of experimental data were used to validate the present model.

The first experiment (Diana et al., 1996) was conducted for 328 days at the Ayutthaya Freshwater Fisheries Station located at Bang Sai, Thailand. Each pond was fertilized with urea and triple superphosphate (TSP) at rates of 28 kg N and 7 kg P ha^{-1} wk^{-1}, and stocked at three fish m^{-2} with 8- to 10-g, sex-reversed male Nile tilapia on 15 January 1993. Five treatments, which included three ponds per treatment, received first feeding at 50 g, 100 g, 150 g, 200 g, and 250 g. The growth of Nile tilapia was simulated at the following fertilization stages: 29, 71, 141, 169, and 225 days for each of the above treatments. The second experiment (Knud-Hansen et al., 1993) was conducted for 146 days at the Ayutthaya Freshwater Fisheries Station. Five treatments with three replications received 20, 60, 100, 140, and 180 kg chicken manure (dry weight) ha^{-1} wk^{-1} and were supplemented with urea and TSP to give all treatments N and P inputs of 28 and 7 kg ha^{-1} wk^{-1}, respectively. Each pond was stocked at 1.6 fish m^{-2}

with 13- to 16-g, sex-reversed male Nile tilapia on 12 October 1989. Experimental ponds were not aerated or mixed artificially during the culture period. From the experiments the following initial values and input variables were used:

1. initial mean body weight (g);
2. stocking densities (fish m^{-2});
3. survival rates (%);
4. surface area (m^2) and volume (m^3) of ponds;
5. monthly measured DO concentrations at dawn (mg l^{-1});
6. biweekly measured water temperature (°C), pH, NH_3-N (mg l^{-1}), total NO_2-N and NO_3-N (mg l^{-1}), soluble reactive phosphorus (mg l^{-1}), alkalinity (mg $CaCO_3$ l^{-1}) at 0900-1000 hr.

DIN and DIP were estimated based on the total dissolved inorganic nitrogen and phosphorus levels in fertilizers and background levels in water. These estimates assumed that DIP changed linearly between biweekly water quality measurements and assuming that DIN and DIP diminished linearly to measured levels after adding fertilizers and then remained at those levels until the next fertilization. To calculate dissolved inorganic nitrogen and phosphorus, all nitrogen and phosphorus contents in inorganic fertilizers were assumed to be dissolved in inorganic forms. Based on the study by Nath (1992, cited by Nath and Lannan, 1993), percentages of dissolved inorganic nitrogen and phosphorus in chicken manure were assumed to be 60% and 80% of total nitrogen and phosphorus, respectively.

Standing crop of Nile tilapia (*B*) was estimated by the simulated daily mean weight and the number of Nile tilapia surviving. It was assumed that all mortality of Nile tilapia occurred at stocking.

Sensitivity Analysis

Sensitivity analysis was carried out to evaluate relative magnitudes of the effects of model parameters or variables on Nile tilapia growth by comparing the percentage of changes in growth when varying parameters or variables by 10% about a baseline value (Table 1). For the baseline simulation the following mean values from the above two experiments were used: initial fish size was 13 g; survival rate was 88%; water temperature was 28.5°C; DO was 3 mg l^{-1}; alkalinity was 85 mg $CaCO_3$ l^{-1}; NH_3-N was 0.65 mg l^{-1}; NO_2+NO_3-N was 0.55 mg l^{-1}; soluble reactive phosphorus was 0.20 mg l^{-1}; pH was 8.1; fertilization rate was 28 kg N and 7 kg P ha^{-1} wk^{-1}. All the above values were held constant for the entire baseline simulation. In order to determine the effects of DO and UIA on growth, the value of DO was set just below its critical limit (0.9 mg l^{-1}) and UIA was set just above its critical limit (0.07 mg l^{-1}).

Results

The simulated growth curves fit closely to the observed data in 15 ponds for each experiment (Figures 1 and 2). The model detected the growth variation within each treatment with the same N and P inputs and showed that the variation was caused mainly by the alkalinity differences among ponds. This indicated that carbon was a limiting nutrient. In each treatment growth was greater in ponds with higher alkalinity. Under the model assumptions, primary production was limited by carbon during 55 to 96% of the culture period of the first experiment and 66 to 99% of the culture period of the second experiment. Ponds where primary production was carbon-limited for greater portions of the culture period demonstrated poor growth. When predicted and observed final weights were compared using Spearman's Rank Correlation Coefficient (r_s), they were significantly correlated ($r_s = 0.84$, $df = 28$, $P < 0.05$). The predicted and observed mean weights were also fitted by simple linear regression ($y = -0.17 + 1.02x$, $r^2 = 0.89$, $df = 238$, $P < 0.05$, Figure 3). Statistical testing of the slope (1.02) and the y-intercept (-0.17) of the regression line revealed that there was no significant departure from a slope of 1.0 ($P > 0.05$) or from a y-intercept of 0 ($P > 0.05$), indicating agreement between predicted and observed values.

The parameters listed in decreasing order of sensitivity are as follows: m, a, b, h, s, n, k_{min}, and j (Table 1). Parameters related to net energy from feeding activity were more sensitive than parameters related to fasting catabolism. Results of a sensitivity analysis for five key variables (Table 2) showed that tilapia growth was most sensitive to food availability when DO was above its critical limit, but was most sensitive to DO when it was below the critical limit. UIA became the third most sensitive variable for Nile tilapia growth when UIA was limited, although sensitivity (about 0.45 for a 10% change) was low. Also, growth was more sensitive to DO than UIA. Water temperature was the least sensitive variable in the model.

Table 1. Sensitivity analysis of model parameters with no limiting factors (None) or DO or UIA as a limiting factor. Parameters are ranked according to mean absolute magnitudes of the percent change of simulated final mean weight with no limiting factors. Negative values indicate that fish weight decreased with an increase in parameter value.

Parameter	**Percent Change of Simulated Final Mean Weight**					
	+10% for Parameter			-10% for Parameter		
	None	*DO Limiting*	*UIA Limiting*	*None*	*DO Limiting*	*UIA Limiting*
Exponent of body weight for net anabolism (m)	32.23	31.55	32.20	-22.64	-22.28	-22.62
Fraction of food assimilated that is used for feeding catabolism (a)	-9.69	-9.77	-9.69	9.46	9.56	9.47
Efficiency of food assimilation (b)	8.40	8.48	8.41	-8.58	-8.65	-8.58
Coefficient of food consumption (h)	8.40	8.48	8.41	-8.58	-8.65	-8.58
Coefficient of food proportionality (s)	6.60	6.47	6.59	-6.84	-6.72	-6.83
Exponent of body weight for fasting catabolism (n)	-2.20	-2.20	-2.20	1.50	1.51	1.50
Coefficient of fasting catabolism (k_{min})	-0.44	-0.46	-0.44	0.45	0.46	0.45
Constant to describe temperature effects on catabolism (j)	-0.08	-0.08	-0.08	0.08	0.08	0.08

Table 2. Sensitivity analysis of key model variables affecting fish growth when there are no limiting factors (None) or only DO or UIA as a limiting factor. Variables are ranked according to mean absolute magnitudes of the percent changes of simulated final mean weight with no limiting factors. Negative values indicate that fish weight decreased with an increase in parameter value.

Variable	**Percent Change of Simulated Final Mean Weight**					
	+10% for Variable			-10% for Variable		
	None	*DO Limiting*	*UIA Limiting*	*None*	*DO Limiting*	*UIA Limiting*
Food Availability	6.60	6.47	6.59	-6.84	-6.72	-6.83
Initial Tilapia Size	0.56	0.66	0.56	-0.58	-0.69	-0.59
Temperature	-0.24	-0.24	-0.24	0.24	0.24	0.24
DO	0	12.66	0	0	-13.05	0
UIA	0	0	-0.45	0	0	0.45

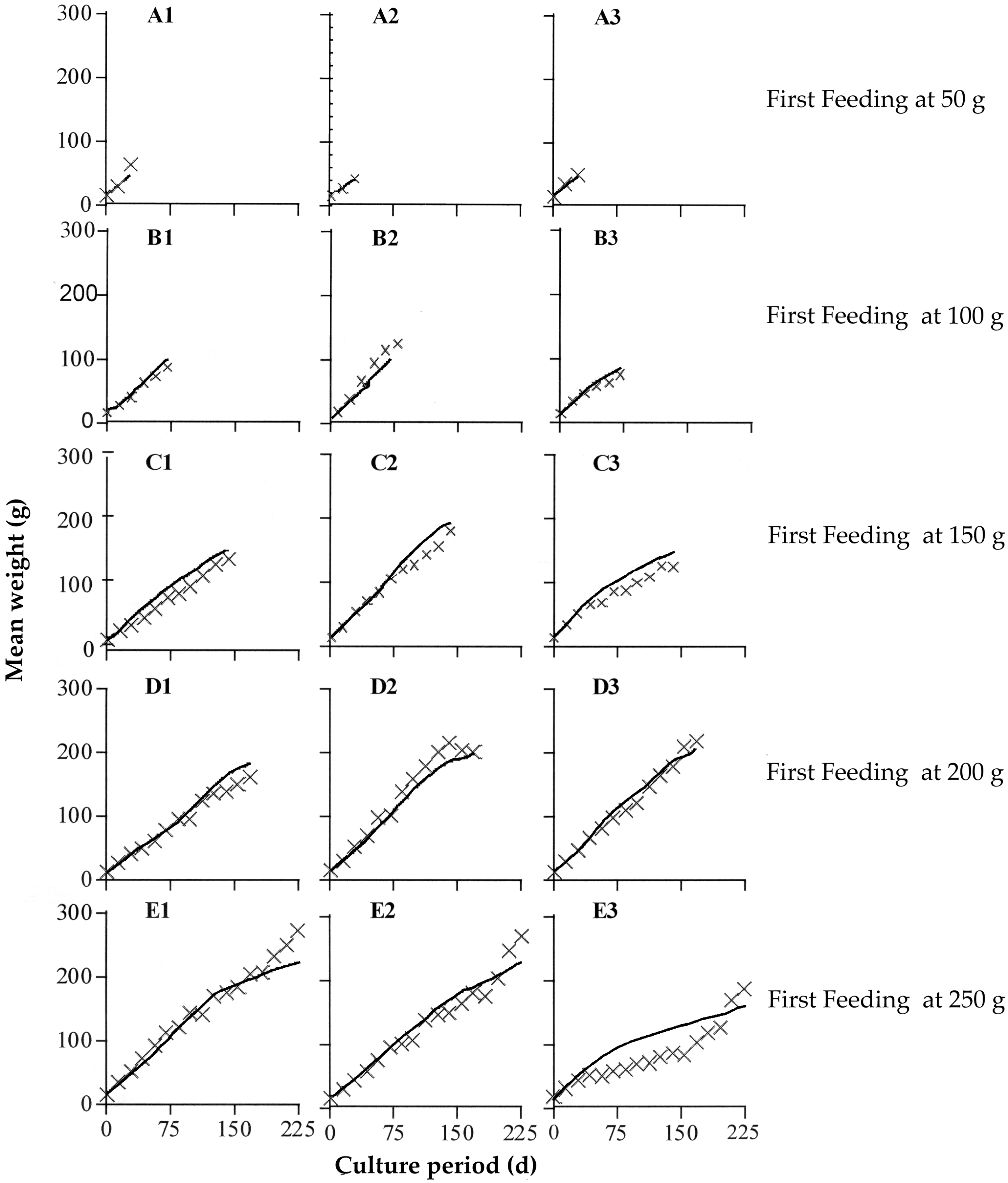

Figure 1. Comparison of Nile tilapia growth predicted by the model (line) with that observed (x) during the fertilization stage of the experiment of Diana et al. (1996). From the top down, each row (A through E) of graphs represents the treatments with first feeding at 50, 100, 200, and 250 g, respectively.

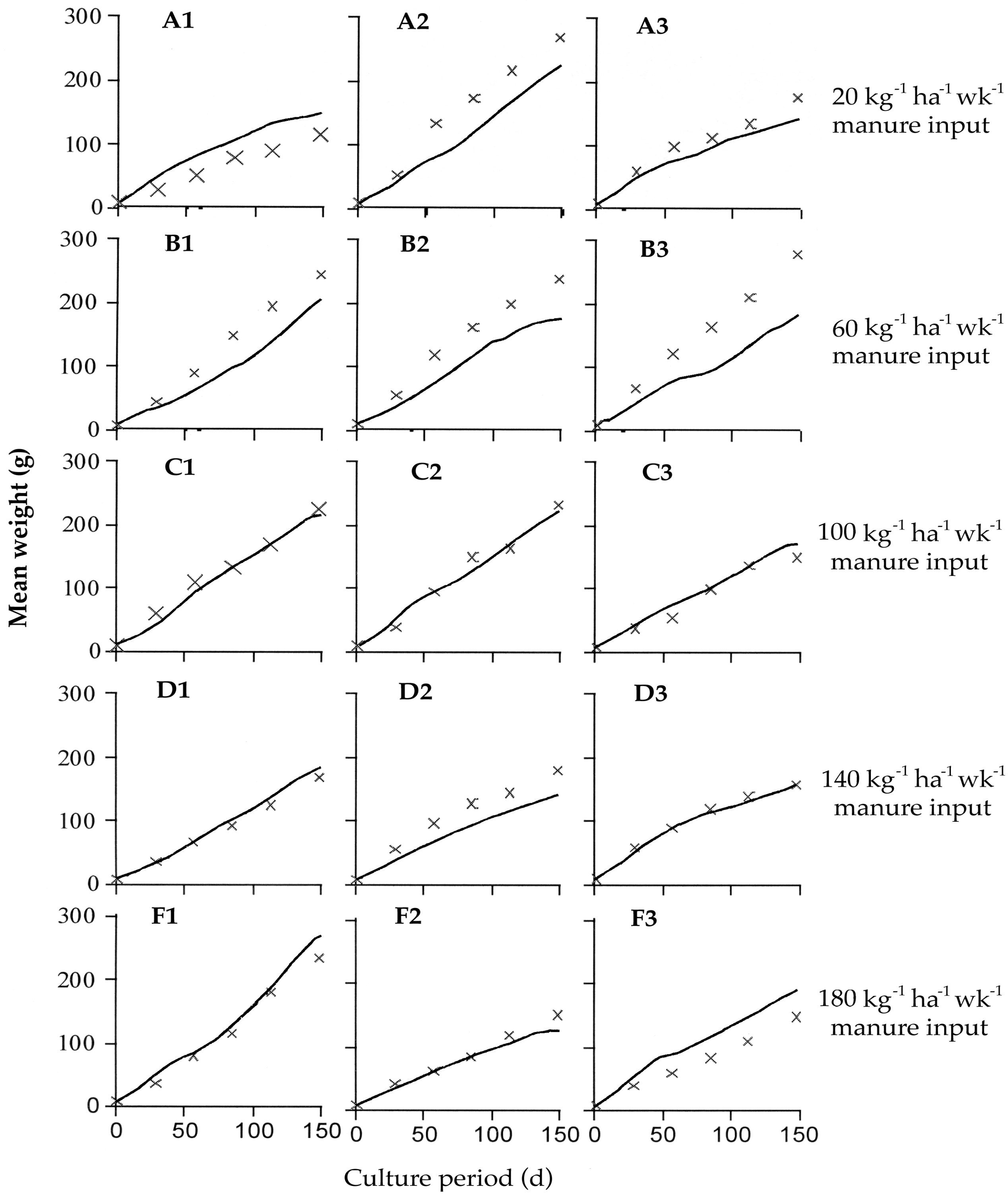

Figure 2. Comparison of Nile tilapia growth predicted by the model (line) with that observed (x) during the experiment of Knud-Hansen et al. (1989). From the top down, each row (A through E) of graphs represents the treatments with chicken manure inputs at 20, 60, 100, 140, and 180 kg ha^{-1} wk^{-1}, respectively.

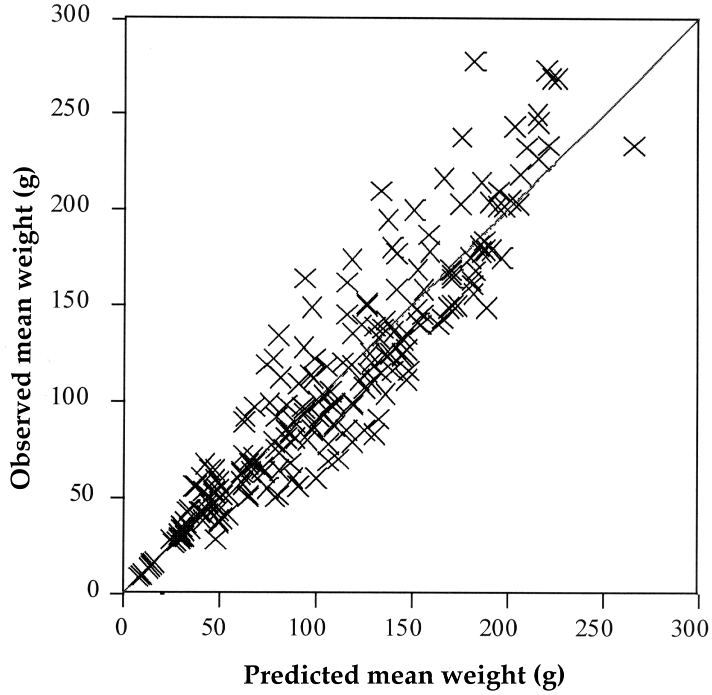

Figure 3. Comparison between predicted and observed mean weight of Nile tilapia in 30 ponds at Ayutthaya, Thailand. The line represents values where observed and predicted values are equal.

Discussion

A new bioenergetics growth model was validated using Nile tilapia growth data in 30 ponds receiving either only inorganic fertilizers (urea and TSP) or different combinations of chicken manure plus inorganic fertilizers. The strength of this model in comparison with previous models (Liu and Chang, 1992; Nath et al., 1993; Bolte et al., 1995) is that it is able to estimate the relative feeding level parameter which describes food availability to Nile tilapia. In the present model, Ivlev's (1961) relative feeding level based on fish number and food concentrations was modified to be a function of fish standing crop and potential net primary productivity estimated by limiting nutrients. Liu and Chang (1992) estimated relative feeding level (Ivlev, 1961) using a fertilizer richness parameter that corresponded to the amount of chicken manure added to the ponds; however, it was difficult to extend this fertilizer richness parameter for use in ponds receiving other fertilizers (Bolte et al., 1994). Nath et al. (1993) expressed the relative feeding level as a function of fish stocking density; the relationship between relative feeding levels and stocking densities of a red variant of *Oreochromis niloticus* fed to satiation with commercial feed (Zonneveld and Fadholi, 1991) was used for this estimation. However, Nath et al. (1993) did not consider nutrient inputs and fish standing crop when estimating relative feeding level. On the other hand, Bolte et al. (1994) expressed the relative feeding level as a ratio of fish critical standing crop to actual standing crop in a pond, but several studies have suggested that the critical standing crop either did not exist for tilapia or occurred before the first biweekly or monthly fish sampling (Zonneveld and Fadholi, 1991; Green, 1992; Diana et al., 1994; Diana et al., 1996). Thus, compared with the above previous models, the present model provides a more reasonable basis for estimating relative feeding level and the effects of fertilization practice on natural food availability and, ultimately, on Nile tilapia growth.

Among some 19 elements which are known to be required by primary producers in aquatic food webs (Wetzel, 1983), phosphorus and nitrogen have received the greatest attention relative to the use of fertilizers to promote fish yields (Boyd, 1982). The present model has detected growth variations that are due to dissolved inorganic carbon, which has limited Nile tilapia growth in ponds that have received identical, high inputs of nitrogen and phosphorus. This is consistent with results reported by McNabb et al. (1988) and Knud-Hansen et al. (1993). McNabb et al. (1988) suggested that dissolved inorganic carbon may be one cause of growth variation in ponds with the same loading rates of phosphorus and/or nitrogen. Furthermore, Knud-Hansen et al. (1993) reported that there was a significant linear correlation between mean alkalinity and mean net primary productivity and, in turn, between mean alkalinity and net yield of Nile tilapia. However, reasons were unclear as to why alkalinity steadily diminished in some ponds (Knud-Hansen et al., 1993). Simulation results of the present model accurately predicted fish growth without considering the role of manure-derived detritus as a food source. This finding supports the conclusions of Schroeder and Buck (1987) and Knud-Hansen et al. (1993), who reported that manure-derived detritus had only a minor influence on tilapia production. In the ponds with low alkalinity, the accumulation of dissolved inorganic nitrogen and phosphorus caused the low utilization efficiency of fertilizers and reduced water quality (concentrations of NH_3 were high and DO concentrations were low). In order to maximize nutrient efficiency while minimizing production costs and the development of adverse environmental conditions, research should focus on carbon utilization and the balance of nitrogen, phosphorus, and carbon inputs.

The sensitivity analysis for parameters produced results similar to Cuenco et al. (1985); food consumption parameters were more critical than metabolism parameters. Among all parameters, *m*, the exponent of body weight for anabolism, was the most sensitive parameter affecting Nile tilapia growth. Liu and Chang (1992) reported that *n*, the exponent of body weight for fasting catabolism, was the most sensitive parameter in their model. They used a much greater value of *k* than in the present model, which might overemphasize fasting catabolism as a component of total metabolism. Water temperature in the present model was the least sensitive parameter, a result that was consistent with the observations by Yi (1997) that water temperature did not seem to be limiting to Nile tilapia growth in tropical, shallow ponds.

Several model refinements should be implemented once the necessary data is collected. The threshold concentrations of DIN or DIP, below which nitrogen and phosphorus are not available for photosynthesis should be determined. In the present model the efficiency of food assimilation (*b*), the third most sensitive parameter was assumed to be constant in the absence of experimental data for efficiency of food assimilation at different temperatures for Nile tilapia (Nath et al., 1993). However, other studies have indicated that *b* decreases with increased food intake for Nile tilapia (Meyer-Burgdorff et al., 1989) and that other factors such as temperature also influence *b* (Caulton, 1982). Additional research should be conducted to further define this parameter. Moreover, the model should be reparameterized to simulate the growth of other fish species cultured in different environments.

Anticipated Benefits

In this model, the growth of Nile tilapia in fertilized ponds has been linked directly to limiting nutrients and fish standing crop which are the bases for the estimation of naturally available foods. The model indicates that growth variations in ponds receiving the same nitrogen and phosphorus inputs were caused by carbon limiting primary production. Model results will improve our understanding of aquaculture pond ecosystems and will be useful for the optimization of fertilizer utilization.

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A Bioenergetics Growth Model for Nile Tilapia (*Oreochromis niloticus*) in a Cage-Cum-Pond Integrated Culture System

Thailand Special Topics Research 2

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Introduction

Integrated aquaculture systems have not been adequately studied because of their complexity (Edwards et al., 1988). While aquaculture research has provided a great deal of information on pond dynamics over the past decades, there has been relatively little effort toward integrating that information into a meaningful and consistent description of pond production systems (Cuenco et al., 1985a). Computer modeling is a valuable tool for the analysis of complex systems (Cuenco, 1989) and is becoming an important component of research efforts to improve our understanding of aquaculture pond ecosystems and to develop management practices to optimize resource utilization (Piedrahita, 1988).

Nile tilapia is one of the most popular cultured species in many tropical countries such as Thailand. Various growth models have been developed for this species (Liu and Chang, 1992; Nath et al., 1994; Bolte et al., 1995; Yi, submitted); however, these models are for Nile tilapia cultured primarily in fertilized ponds with or without supplemental feeding. Modeling techniques have yet to be applied to integrated aquaculture such as a cage-cum-pond system, in which large Nile tilapia are fattened in cages and smaller Nile tilapia are nursed in open water to utilize wastes derived from cages (Yi et al., 1996; Yi, 1997).

The purpose of this study was to develop a bioenergetics growth model for Nile tilapia in both cages and open-ponds of the cage-cum-pond integrated culture system. This was accomplished through the synthesis of currently available information in fish physiology and pond dynamics and the subsequent modification of current models to evaluate the effects of body size, temperature, dissolved oxygen (DO), unionized ammonia (UIA), and food availability on the growth of both caged and open-pond Nile tilapia. This model will allow aquaculture managers to evaluate appropriate management strategies and predict outcomes in the cage-cum-pond integrated culture system.

The Models

Model Development

The model was written using a dynamic modeling language called STELLA® II (High Performance Systems, Inc. 1990) based on a model developed by Ursin (1967). The model used a time step of one day, and the equations were solved using a 4th-order Runge-Kutta numerical integration method.

Adding artificial feed to a pond has a fertilizing effect and thus increases the amount of natural foods in the pond (Cuenco et al., 1985b), making both artificial feed and natural foods are available to fish. Thus, based on Ursin's work (1967), growth (dW/dt in g d^{-1}) of both caged and open-pond Nile tilapia in a cage-cum-pond integrated culture system (Yi, et al., 1996; Yi, 1997) can be expressed as follows:

$$dW/dt = [b_a\,(1 - a_a)\,dR_a/dt] + [b_n\,(1 - a_n)\,dR_n/dt] - kW^n \quad (1)$$

where

b_a = efficiency of artificial feed assimilation (dimensionless),

a_a = fraction of the assimilated artificial feed used for feeding catabolism (dimensionless),

dR_a/dt = daily ration of artificial feed (g d^{-1}),

b_n = efficiency of natural food assimilation (dimensionless),

a_n = fraction of assimilated natural foods used for feeding catabolism (dimensionless),

dR_n/dt = daily ration of natural foods (g d^{-1}),

k = coefficient of fasting catabolism ($g^{1-n}\,d^{-1}$),

W = fish body weight (g), and

n = exponent of body weight for fasting catabolism (dimensionless).

Key variables affecting fish growth are fish size, DO, UIA, water temperature, photoperiod, and food availability. The impact of these variables on growth is mediated through their effect on food intake and they are of an interactive nature (Brett, 1979; Cuenco et al., 1985a). Due to warm climate and the shallowness of most tropical fish ponds, temperature and photoperiod are not likely to limit food consumption. Thus, the daily ration of artificial feed and natural foods can be expressed as:

$$dR_a/dt = \delta \upsilon F_a \quad (2a)$$

$$dR_n/dt = \delta \upsilon F_n \quad (2b)$$

where

δ = DO factor (dimensionless),

υ = UIA factor (dimensionless),

F_a = availability of artificial feed (g d^{-1}),

F_n = availability of natural foods (g d^{-1}).

Based on the previous work (Cuenco et al., 1985a), the functions d and u describe the effects of DO and UIA on food intake and are expressed as:

$$\delta = 1.0 \quad \text{if DO} > DO_{crit} \quad (3a)$$

$$\delta = (DO - DO_{min})/(DO_{crit} - DO_{min}) \quad \text{if } DO_{min} \le DO \le DO_{crit} \quad (3b)$$

$$\delta = 0.0 \quad \text{if DO} < DO_{min} \quad (3c)$$

$$\upsilon = 1.0 \quad \text{if UIA} < UIA_{crit} \quad (4a)$$

$$\upsilon = (UIA_{max} - UIA)/(UIA_{max} - UIA_{crit}) \quad \text{if } UIA_{crit} \le UIA \le UIA_{max}) \quad (4b)$$

$$\upsilon = 0.0 \quad \text{if } UIA > UIA_{max} \quad (4c)$$

where

DO_{min} = a minimum DO level (mg l^{-1}),

DO_{crit} = a critical DO limit (mg l^{-1}),

UIA_{max} = a maximum UIA level (mg l^{-1}),

UIA_{crit} = a critical UIA level (mg l^{-1}).

Food consumption is not affected when DO is above DO_{crit} or when UIA is below UIA_{max}. Decreases in food consumption are more or less linear with decreasing DO or increasing UIA until DO_{min} or UIA_{max} is reached. Fish do not feed when DO is below DO_{min} or UIA is above UIA_{max} (Cuenco et al., 1985a).

Artificial feed is given to fish in many different ways; however, not all feed is available to fish. The actual amount of artificial feed that fish consume depends on many factors, such as physical quality of the feed and application methods. Thus, a parameter for feeding efficiency *(q)* is introduced in the model to describe the amount of given artificial feed that fish are able to consume. In the cage-cum-pond integrated culture system (Yi et al., 1996; Yi, 1997), caged tilapia were given a high quality floating pelleted feed at rates based on sampled body weight; however, a small portion of the feed was probably knocked out of cages due to vigorous swimming activity of caged tilapia (Collins, 1971; Coche, 1979; McGinty, 1991; Yi, 1997). I assumed that the amount of natural foods consumed by caged tilapia is negligible, so the availability of both artificial feed and natural foods for caged tilapia can be expressed as:

$$F_{ac} = q_c \, f_c \, W_s \quad (5a)$$

$$F_{nc} = 0 \quad (5b)$$

where

F_{ac} = availability of artificial feed to caged tilapia (g d^{-1}),

q_c = feeding efficiency on artificial feed for caged tilapia,

f_c = feeding rates (BWD),

W_s = sampled body weight of caged tilapia (g),

F_{nc} = availability of natural foods to caged tilapia (g d^{-1}).

Thus, based on equations 2a and 2b, the food quantity consumed by caged tilapia can be described as follows:

$$dR_{ac}/dt = \delta_c \upsilon_c q_c f_c W_s \quad (6a)$$

$$dR_{nc}/dt = 0 \quad (6b)$$

where

dR_{ac}/dt = daily ration of artificial feed for caged tilapia (g d^{-1}),

δ_c = DO factor for caged tilapia,

υ_c = UIA factor for caged tilapia,

dR_{nc}/dt = daily ration of natural foods for caged tilapia (g d^{-1}).

Fish confined in cages use less energy for feeding activity compared to fish at large in ponds. Thus, a parameter (*e*) is introduced to describe the reduction of food energy used by caged fish for feeding catabolism compared with pond fish. Then, equation 1 can be re-written for growth rates of caged tilapia (dW_c/dt) as follows:

$$dW_c/dt = b_a (1 - a_a e) \delta_c \upsilon_c q_c f_c W_s - kW_c^n \quad (7)$$

where

e = coefficient of reduction of food energy used by caged tilapia for feeding catabolism (dimensionless) and

W_c = body weight of caged tilapia (g).

The total waste feed from cages, including that knocked out of cages and that uneaten by caged tilapia due to low DO and/or high UIA, is available to open-pond tilapia. Thus, the daily availability of artificial feed to individual open-pond tilapia is expressed as follows:

$$F_{ap} = f_c W_s (1 - \delta_c \upsilon_c q_c) (N_c/N_p) \quad (8)$$

where

F_{ap} = availability of artificial feed to open-pond tilapia (g d^{-1}),

N_c/N_p = ratio of total number of surviving tilapia in cages to that of surviving tilapia in open pond, which divides total wasted feed from cages evenly to each open-pond tilapia.

The availability of natural foods to open-pond tilapia is based on the modeling rations proposed by Ursin (1967) and expressed as:

$$F_{np} = f_p W_p^m \quad (9)$$

where

F_{np} = availability of natural foods to open-pond tilapia (g d^{-1}),

f_p = relative feeding level ($0 < f_p < 1$, dimensionless),

W_p = body weight of open-pond tilapia (g),

m = exponent of body weight for net anabolism.

Yi (submitted) modified Ivlev's (1961) equation for the relative feeding level, and expressed it to be the function of potential net primary productivity (PNPP) and standing crop of Nile tilapia as the following:

$$f_p = 1 - \exp(-s\,P\,/B) \quad (10)$$

where

s = coefficient of food proportionality (dimensionless),

P = PNPP (g C m^{-3} d^{-1}),

B = standing crop of Nile tilapia (g m^{-3}).

Based on Lannan (1993), Yi (submitted) estimated the parameter, P, using the following:

$$P = \mathrm{Min}(P_c, P_n, P_p) \quad (11)$$

$$P_c = 12\lambda\,(A\,/50)\,\{[(H^+)^2 / k_1 + H^+ + k_2] \,/\, (H^+ + 2\,k_2)\} \quad (12)$$

$$k_1 = (T/15 + 2.6)\,10^{-7} \quad (12a)$$

$$k_2 = (T/10 + 2.2)\,10^{-11} \quad (12b)$$

$$P_n = 40\,D_n/7 \quad (13)$$

$$P_p = 40\,D_p \quad (14)$$

where

P_c = PNPP derived from dissolved inorganic carbon (DIC) (g C m^{-3} d^{-1}),

P_n = PNPP derived from dissolved inorganic nitrogen (DIN) (g C m^{-3} d^{-1}),

P_p = PNPP derived from dissolved inorganic phosphorus (DIP) (g C m^{-3} d^{-1}),

λ = efficiency of carbon fixation (dimensionless),

A = alkalinity (mg $CaCO_3$ l^{-1}),

H^+ = hydrogen ion concentration (moles l^{-1}),

k_1 = the first dissociation constant for carbonate/bicarbonate system,

k_2 = the second dissociation constant for carbonate/bicarbonate system,

T = water temperature (°C),

D_n = DIN (mg N l^{-1}), and

D_p = DIP (mg P l^{-1}).

The constants 12 and 50 in equation 12 are gram equivalent weights of C and $CaCO_3$, respectively, and 40 and 7 in equations 13 and 14 are based on carbon:nitrogen:phosphorus ratios of 40:7:1 by weight (Round, 1973; Vallentyne, 1974; Wetzel, 1983).

Thus, availability of natural foods to individual, open-pond tilapia (F_{np}) is expressed as follows:

$$F_{np} = [1 - \exp(-s\,P/B)]\,W_p^m \quad (15)$$

Experimental evidence suggests that tilapias under culture conditions prefer artificial feed to natural foods (Schroeder, 1978). Therefore, it is assumed that Nile tilapia will take artificial feed independently of the concentration of natural food resources, and that they will consume natural foods whenever they can not meet their daily food intake requirements from artificial feed (Jamu and Piedrahita, 1996). Thus, the daily ration of artificial feed (dR_{ap}/dt) and natural foods (dR_{np}/dt) for open-pond tilapia can be expressed as follows:

$$dR_{ap}/dt = F_{ap}\, q_p \qquad dR_{np}/dt = h\,[\delta_p\, \upsilon_p\, (F_{ap}+F_{np}) - F_{ap}]$$

$$\text{if } F_{ap} < \delta_p\, \upsilon_p\, (F_{ap}+F_{np}) \qquad (16a)$$

$$dR_{ap}/dt = F_{ap}\, q_p \qquad dR_{np}/dt = 0$$

$$\text{if } F_{ap} = \delta_p\, \upsilon_p\, (F_{ap}+F_{np}) \qquad (16b)$$

$$dR_{ap}/dt = \delta_p\, \upsilon_p\, q_p\, (F_{ap}+F_{np}) \qquad dR_{np}/dt = 0$$

$$\text{if } F_{ap} > \delta_p\, \upsilon_p\, (F_{ap}+F_{np}) \qquad (16c)$$

where

q_p = feeding efficiency on artificial feed for open-pond tilapia (dimensionless),

h = coefficient of food consumption (g^{1-m} day^{-1}),

$F_a + F_n$ = total daily food availability to open-pond tilapia, and

$\delta_p\, \upsilon_p\, (F_a + F_n)$ = total daily ration.

Instead of determining the maximum daily ration of open-pond tilapia, growth attainable in one day for open-pond tilapia is set at maximum growth (4.16 g day^{-1}), which was observed for Nile tilapia fed with pelleted feed in chemically fertilized ponds in an experiment reported by Diana et al. (1996). Thus, growth rates (dW_p/dt) of open-pond tilapia can be expressed as follows:

$$dWp/dt = b_a\,(1 - a_a)\, dR_{ap}/dt + b_n\,(1 - a_n)\, dR_{np}/dt - k\, W_p^{\,n} \qquad (17)$$

$$dW_p/dt \le 4.16 \qquad (17a)$$

Ursin (1967) and Sperber et al. (1977) assumed that the coefficient of catabolism (k) increases exponentially with temperature. Nath et al. (1994) modified this exponential form to include the minimum temperature below which the fish species can not survive (T_{min}) in the following equation:

$$k = k_{min} \exp\,[\,j\,(T - T_{min})] \qquad (18)$$

where

k_{min} = coefficient of fasting catabolism (g^{1-n} day^{-1}) at T_{min},

j = constant to describe temperature effects on catabolism (1/°C).

Parameter Estimation

Nath et al. (1993) analyzed oxygen consumption data of fasting Nile tilapia and estimated the mean for n to be 0.81. Ursin (1967) suggested that the exponent m approximated to 0.67. These two values were used in the present model.

For Nile tilapia feeding on natural foods in fertilized ponds, I assumed the efficiency of natural food assimilation (b_n) and the fraction of assimilated food used for feeding catabolism (a_n) to be 0.62 and 0.53 (Nath et al., 1994), respectively; these values were based on the work reported by Meyer-Burgdorff et al. (1989). The energy cost of feeding activity for fish fed with dry pellet diets was found to be 14.9% of gross energy ingested (Schalles and Wissing, 1976), implying that the parameter a_a for artificial feed is (0.149)/(b_a). By regression analysis of data on metabolic rates of Nile tilapia at swimming speeds from 0 to 60 cm s^{-1} (Farmer and Beamish, 1969), the parameter e was estimated to be 0.327. Assuming that tilapia in cages performed no active swimming activity and that tilapia at large had an average metabolic rate from the range of swimming speeds cited above. Then, parameters, b_a and a_a, were estimated to be 0.946 ± 0.03 and 0.158 ± 0.005, respectively, using growth data from caged tilapia in two randomly selected ponds from 30 experimental ponds of a cage-cum-pond integrated culture system (Yi, et al., 1996; Yi, 1997). For floating pellets, I assumed that all feed provided could be eaten by tilapia at large in ponds, thus, feeding efficiency with artificial feed for open-pond tilapia (q_p) was 1.0. For caged tilapia, I assumed that 5% of the pelleted feed was knocked out of cages, thus, feeding efficiency for caged tilapia (q_c) was 0.95. The values of parameters h and s were assumed to be 0.8 (Bolte et al., 1995) and 17.31 (Yi, submitted), respectively, in this model for Nile tilapia at large in ponds.

Based on laboratory experiments with Nile tilapia (Gannam and Phillips, 1993) T_{min} appears to be about 15°C. Nath et al. (1994) used data on fasting Nile tilapia from Satoh et al. (1984) to estimate k_{min} and j to be 0.00133 and 0.0132, respectively.

Abdalla (1989) investigated the effects of ammonia on Nile tilapia growth and determined that UIA_{max} = 1.40 mg l^{-1} and UIA_{crit} = 0.06 mg l^{-1}. However, DO_{crit} and DO_{min} have not been well defined. Nile tilapia can tolerate low DO and survive in water where only air breathing fish species can exist (Boyd, 1990) because Nile tilapia are able to use atmospheric oxygen when DO concentration drops to less than 1 mg l^{-1} (Chervinski, 1982). The lowest DO concentrations tolerated by Nile tilapia ranged from 0.1 to 0.3 mg l^{-1} under different environmental conditions (Ahmed and Magid, 1968; Magid and Babiker, 1975). Teichert-Coddington and Green (1993) reported that a practical DO threshold for Nile tilapia was not greater than 10% of saturation. Thus, DO_{crit} and DO_{min} for open-pond Nile tilapia used in the present model were 1.0 and 0.3 mg l^{-1}, respectively. Fish contained at high densities in cages are unable to seek out zones of favorable water quality and may be more susceptible to fluctuations in pond water quality, particularly low DO concentrations, than are free-ranging fish (Hargreaves et al., 1991). Therefore, DO_{crit} and DO_{min} for caged Nile tilapia were assumed to be 1.2 and 0.3 mg l^{-1}, respectively.

Data Requirements for Model Validation

Almost all values for parameters used in the present model were derived from the literature. To test the validity of the model, simulated results were compared with independently obtained experimental results which were not used during model development. The data used to validate the present model were collected from three experiments carried out at the Asian Institute of Technology, Thailand from August 1994 to September 1995. These experiments were conducted in 30 earthen ponds (335 m^2 or 395 m^2 in surface area and 330 m^3 in volume) over 90 days to investigate the effects of different stocking densities (30, 40, 50, 60 and 70 fish m^{-3}) of caged Nile tilapia, (one, two and three cages per pond), and the stocking densities of open-pond Nile tilapia (1.4 and 2.0 fish m^{-3}) on growth performance of both caged and open-pond fish (Yi et al., 1996; Yi, 1997). Two of these ponds were randomly selected to estimate parameters b_a and a_a. In the cage-cum-pond integrated culture system, caged tilapia were fed with floating pelleted feed, while growth of open-pond tilapia was dependent solely on the wastes derived from cages. From the experiments, the following initial values and input variables were used:

1. initial mean body weight of both caged and open-pond tilapia (g);
2. stocking densities of caged tilapia and open-pond tilapia (fish m^{-3});
3. survival rates of caged tilapia and open-pond tilapia (%);
4. cage size (m^3) and the number of cages in each pond (cages per pond);
5. surface area (m^2) and volume (m^3) of ponds;
6. contents of moisture, nitrogen, and phosphorus in feed and tilapia;
7. monthly dawn DO concentrations (mg l^{-1});
8. daily water temperature (°C), which was predicted by use of the model described by Nath (1996);
9. biweekly measured pH and alkalinity (mg $CaCO_3$ l^{-1}) between 0900 and 1000 h.

Floating pelleted feed was given daily to caged tilapia at feeding rates (f_c) of 3, 2.5, and 2% body weight during the first, second, and third months, respectively. The daily feed amount ($f_c W_s$) was adjusted based on daily observed mortality and biweekly sampled weight of caged tilapia.

Lin et al. (1988) reported that nitrogen fixation was of considerable magnitude in organically and inorganically fertilized ponds containing Nile tilapia. The mean nitrogen fixation rate in their ponds (0.11 mg N l^{-1} day^{-1}) was used in the present model. Thus, DIN was estimated as the sum of dissolved inorganic nitrogen levels from cage wastes and nitrogen fixation, and DIP was estimated as the dissolved inorganic phosphorus from cage wastes. Nath (1992, cited by Nath and Lannan, 1993) determined that percentages of dissolved inorganic nitrogen and phosphorus in chicken manure were 60 and 80% of total nitrogen and phosphorus, respectively. Without definitive information on the solubility of cage wastes, the same percentages were used in the present model to estimate dissolved inorganic nitrogen and phosphorus levels from cage wastes. The total nitrogen and phosphorus contents in cage wastes were estimated as the difference between quantities of nitrogen and phosphorus contained in given feed and in carcasses of caged tilapia.

Table 1. Sensitivity analysis of model parameters with no limiting factors (None) or with DO or UIA as a limiting factor. Parameters are ranked according to the magnitude of the percentage change of simulated final mean weight for the data category that has no limiting factors (None). Negative values indicate that fish weight decreased with an increase in parameter value.

Parameter	Percentage Change of Simulated Final Mean Weight					
	+10% for Parameter			-10% for Parameter		
	None	*DO Limiting*	*UIA Limiting*	*None*	*DO Limiting*	*UIA Limiting*
CAGED NILE TILAPIA						
b_a = efficiency of assimilation of artificial feed	15.61	11.17	15.52	-13.82	-10.22	-13.75
q_c = feeding efficiency with artificial feed	15.61	11.17	15.52	-13.82	-10.22	-13.75
n = exponent of body weight for fasting metabolism	-2.52	-2.60	-2.52	1.63	1.72	1.63
a_a = fraction of the assimilated artificial feed used for feeding metabolism	-0.80	-0.58	-0.79	0.80	0.58	0.79
e = coefficient of reduction of food energy for feeding catabolism	-0.80	-0.58	-0.79	0.80	0.58	0.79
k_{min} = coefficient of fasting catabolism at T_{min}	-0.44	-0.48	-0.44	0.44	0.48	0.44
j = constant to describe temperature effects on catabolism	-0.09	-0.10	-0.09	0.09	0.10	0.09
m = exponent of body weight for net anabolism	0	0	0	0	0	0
h = coefficient of food consumption	0	0	0	0	0	0
s = coefficient of food proportionality	0	0	0	0	0	0
b_n = efficiency of natural food assimilation	0	0	0	0	0	0
a_n = fraction of assimilated natural foods used for feeding metabolism	0	0	0	0	0	0
q_p = feeding efficiency of open-pond tilapia fed artificial food	0	0	0	0	0	0

The standing crop of open-pond Nile tilapia (B) was estimated from the simulated daily mean weight and the number of open-pond Nile tilapia surviving. It was assumed that all mortality of open-pond Nile tilapia occurred at stocking.

Sensitivity Analysis

Sensitivity analysis was carried out to evaluate the relative magnitude of effects of model parameters or variables on growth of both caged and open-pond tilapia. This was done by comparing the percentage change in growth when varying a parameter or variable by 10% about a baseline value (Tables 1 and 2). For the baseline simulation the following mean values from the above three experiments were used: initial sizes of caged tilapia and open-pond tilapia were 121 g and 28 g, respectively; stocking densities of caged tilapia and open-pond tilapia were 50 fish m^{-3} and 1.7 fish m^{-3}, respectively; survival rates of caged tilapia and open-pond tilapia were 86.2% and 91.5%, respectively; the number of cages per pond was two; feeding rate of caged tilapia was 2.5% BWD; water temperature was

Table 1. Continued.

Parameter	Percentage Change of Simulated Final Mean Weight					
	+10% for Parameter			-10% for Parameter		
	None	*DO Limiting*	*UIA Limiting*	*None*	*DO Limiting*	*UIA Limiting*
OPEN-POND TILAPIA						
q_c = feeding efficiency with artificial feed	-27.46	-6.22	-26.50	3.49	5.44	22.66
m = exponent of body weight for net anabolism	18.38	10.52	18.02	-13.68	-7.77	-13.41
a_n = fraction of assimilated natural foods used for feeding anabolism	-6.37	-3.10	-6.24	6.26	3.06	6.12
b_n = efficiency of natural food assimilation	5.56	2.71	5.43	-5.64	-2.74	-5.52
h = coefficient of food consumption	5.56	2.71	5.43	-5.64	-2.74	-5.52
s = coefficient of food proportionality	4.90	2.71	4.79	-5.04	-2.77	-4.94
b_a = efficiency of assimilation of artificial feed	2.42	8.47	2.74	-2.29	-7.76	-2.59
q_p = feeding efficiency with artificial feed of open-pond tilapia	1.39	5.29	1.55	-1.38	-5.27	-1.56
n = exponent of body weight for fasting catabolism (dimensionless)	-1.55	-2.07	-1.57	1.11	1.43	1.12
k_{min} = coefficient of fasting catabolism at T_{min}	-0.38	-0.44	-0.38	0.38	0.45	0.37
a_a = fraction of the assimilated artificial feed used for feeding metabolism	-0.31	-1.13	-0.35	0.31	1.14	0.35
j = constant to describe temperature effects on catabolism	-0.08	-0.09	-0.08	0.07	0.09	0.07
e = coefficient of reduction of food energy for feeding catabolism	-0.05	-0.15	-0.06	0.04	0.15	0.05

30.5°C; DO was 1.8 mg l^{-1}; alkalinity was 93 mg $CaCO_3$ l^{-1}; pH was 7.4; and UIA was 0.03 mg l^{-1}. All the above values were held constant for the entire baseline simulation. In order to determine the effects of DO and UIA on Nile tilapia growth, the value of DO was set just below its critical limit (0.9 mg l^{-1}) and UIA was set just above its critical limit (0.07 mg l^{-1}).

Results

The simulated growth curves for both caged and open-pond tilapia fit well to observed data in ten treatments each with three replications (Figure 1). Linear regression showed that there was a statistically significant relationship between predicted and observed mean weights for both caged tilapia ($y = 12.10 + 1.02x$, $r^2 = 0.95$, df = 68, $P < 0.05$, Figure 2) and open-pond tilapia ($y = 7.77 + 0.92x$, $r^2 = 0.83$, df = 68, $P < 0.05$, Figure 2). The slope (1.02) and the y-intercept (12.10) of the regression line for caged tilapia were not significantly different from a slope of 1.0 ($P > 0.05$) and a y-intercept of 0 ($P > 0.05$). The same test for open-pond tilapia showed that there was no significant departure of the slope (0.92) from 1.0 ($P > 0.05$), but there was significant departure of the y-intercept (7.77) from 0 ($P < 0.05$). However, Spearman's rank correlation coefficient (r_s)

Table 2. Sensitivity analysis of key model variables affecting fish growth with no limiting factors (None) or with DO or UIA as a limiting factor. Variables are ranked according to mean absolute magnitudes of the percent changes of simulated final mean weight with no limiting factors (None). Negative values indicate that fish weight decreased with an increase in parameter value.

Variable	Percentage Change of Simulated Final Mean Weight					
	+10% for Variable			-10% for Variable		
	None	*DO Limiting*	*UIA Limiting*	*None*	*DO Limiting*	*UIA Limiting*
CAGED NILE TILAPIA						
Artificial Feed Availability	15.61	11.17	15.52	-13.82	-0.22	-13.75
Size of Caged Tilapia	7.61	8.30	7.63	-7.61	-8.29	-7.62
Temperature	-0.18	-0.20	-0.18	0.18	0.19	0.17
DO	0	17.13	0	0	-15.00	0
UIA	0	0	-0.77	0	0	0.77
Natural Food Availability	0	0	0	0	0	0
Size of Open-Pond Tilapia	0	0	0	0	0	0
OPEN-POND TILAPIA						
Artificial Feed Availability	8.68	10.66	8.82	-8.27	-10.06	-8.41
Natural Food Availability	5.56	2.99	5.44	-5.64	-3.02	-5.53
Size of Caged Tilapia	3.35	4.97	3.40	-3.48	-5.01	-3.54
Size of Open-Pond Tilapia	1.87	1.33	1.84	-1.85	-1.32	-1.83
Temperature	-0.15	-0.18	-0.16	0.15	0.18	0.15
DO	0	-3.12	0	0	0.52	0
UIA	0	0	0.97	0	0	-0.98

indicated that predicted and observed final weights of open-pond tilapia were significantly correlated ($r_s = 0.81$, df = 8, $P < 0.05$). When predicted and observed final weights of caged tilapia were compared using Spearman's rank correlation coefficient, they were also significantly correlated ($r_s = 0.80$, df = 8, $P < 0.05$). Therefore, there were agreements between predicted and observed values of both caged and open-pond tilapia.

The model showed that carbon was not a limiting nutrient for primary production in the cage-cum-pond integrated culture. Growth of open-pond tilapia was limited by phosphorus which limited primary production when the total number of tilapia stocked in cages was not greater than 200 fish per pond. With a cage stocking density greater than 200 fish per pond, phosphorus was limiting during the early part of the experiment, but then the limiting nutrient became nitrogen.

The percentage of the culture period during which primary production was limited by nitrogen increased from 0 to 84.4% as the total number of tilapia stocked in cages increased (with resultant increases in artificial feed) from 200 to 600 fish per pond. Nitrogen from biological nitrogen fixation accounted for 44.2 to 74.8% of total nitrogen available for primary production and increased with decreases in the total number of tilapia stocked in cages. Under the model assumptions, pelleted feed accounted for only 13.8 to 14.6% of the growth of open-pond tilapia when DO was above DO_{crit} (1.2 mg l^{-1}) for caged tilapia. However, these percentages ranged from 19.0 to 51.0% when DO was less than 1.2 mg l^{-1}, and increased with an increase in the number of days that DO was below this critical level.

Sensitivity analysis for the parameters (Table 1) showed that parameters for caged tilapia affected

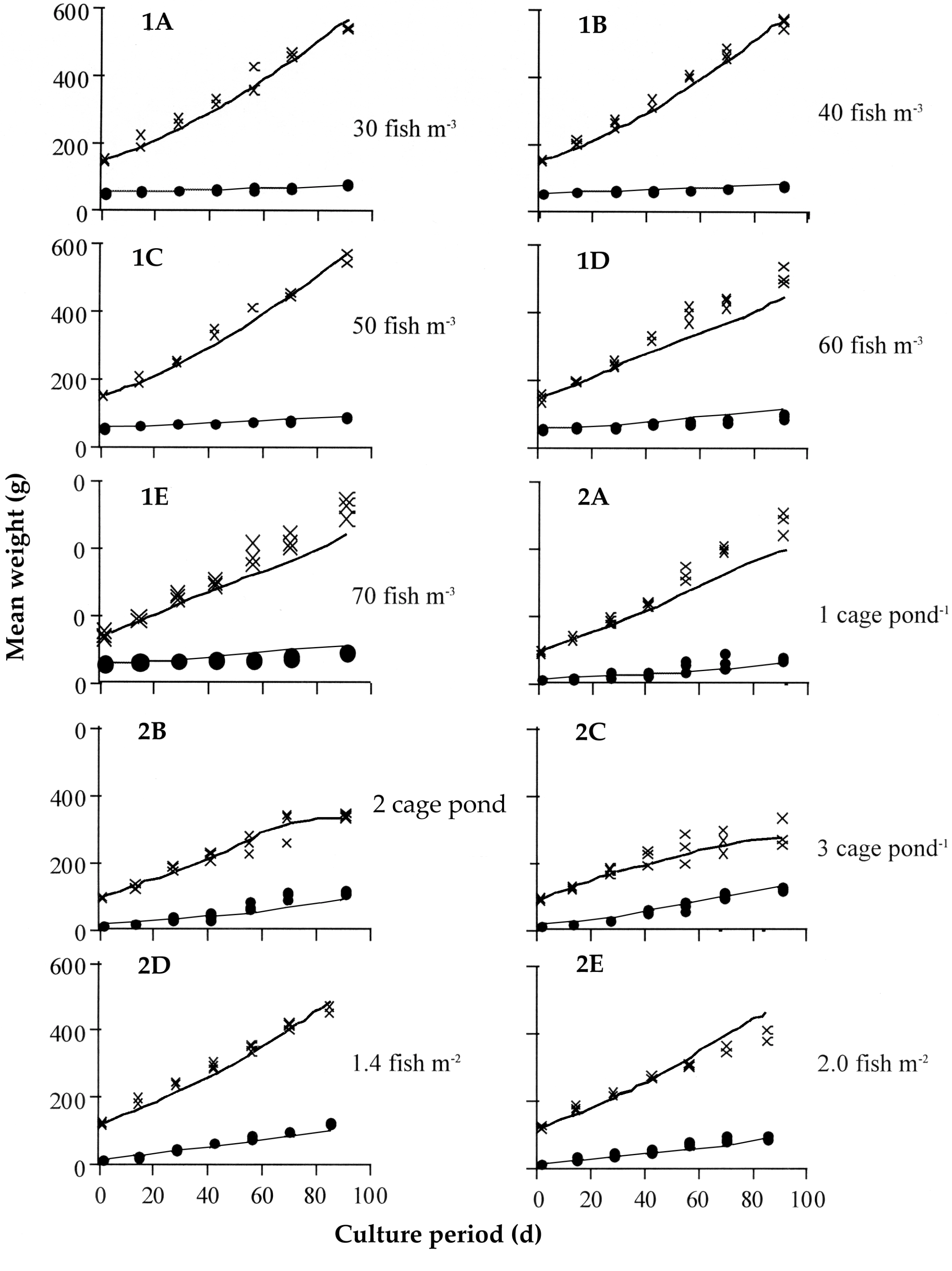

Figure 1. Comparison of model data with the growth of caged (•) and open-pond (x) Nile tilapia (*Oreochromis niloticus*) as recorded by Yi (1997b). Graphs 1A-E represent the treatments for stocking densities of caged tilapia at 30, 40, 50, 60, and 70 fish m^{-3}, respectively. Graphs 2A-C represent the treatments with one, two, or three cages per pond, respectively. Graphs 3A-B represent the treatments for stocking densities of open-pond tilapia at 1.4 and 2.0 fish m^{-2}, respectively.

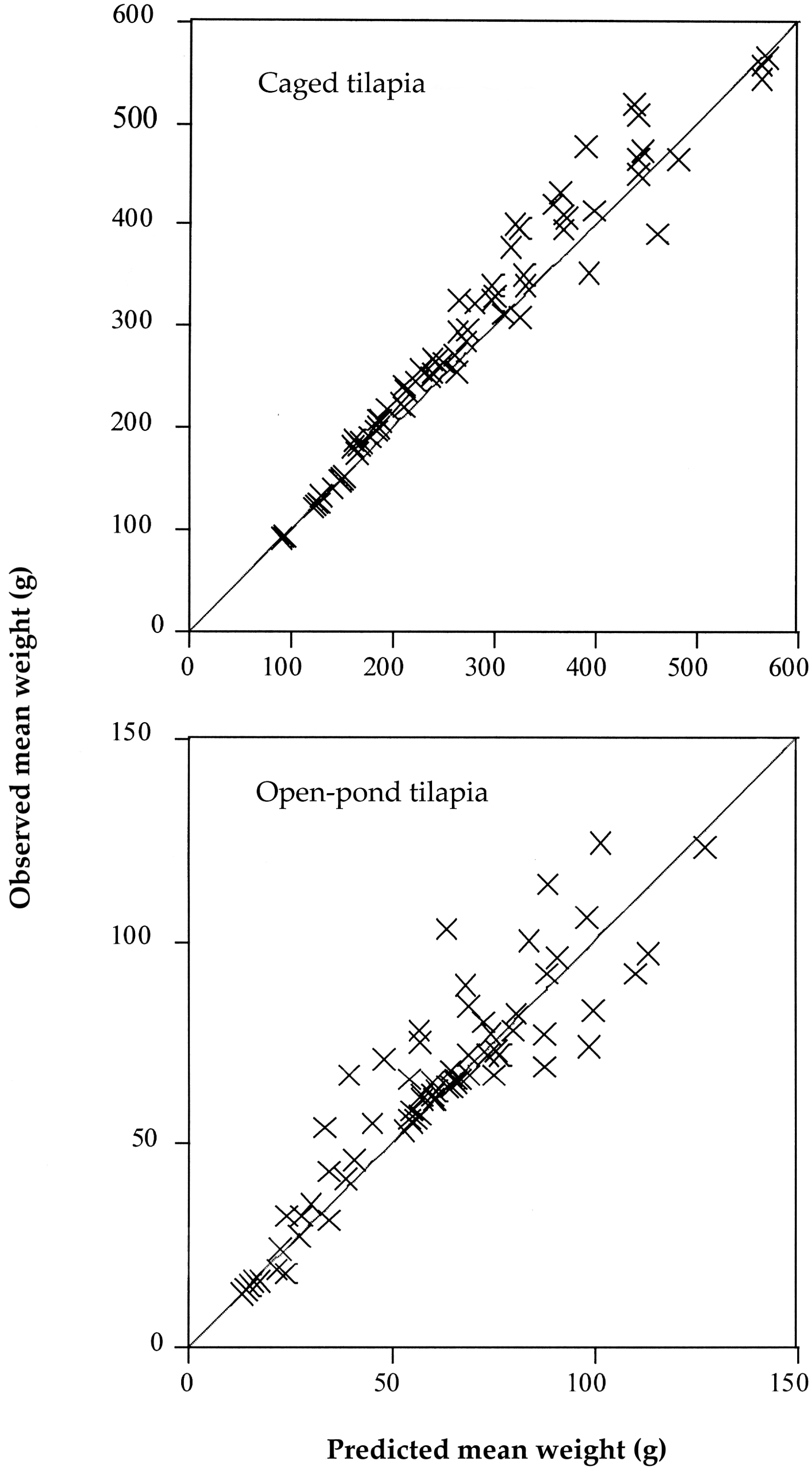

Figure 2. Comparison between predicted and observed mean weights of caged and open-pond tilapia in 28 ponds in the experiments of Yi (1997). The line represents equality (where observed weight equals predicted weight).

growth of open-pond tilapia but not the reverse. The efficiency of artificial feed assimilation (b_a) was the most sensitive parameter influencing growth of caged tilapia. When DO was not a limiting factor for open-pond tilapia (>1.0 mg l^{-1}), the most sensitive parameter affecting growth of open-pond tilapia was the feeding efficiency of caged tilapia (q_c), followed by the exponent of body weight for anabolism (m), which became the most sensitive parameter when DO was limited. The parameters related to net energy from foraging natural foods (a_n, b_n, h, s) were more important for open-pond tilapia than those related to artificial feed (b_a, a_a) when DO was not limited. However, the relative importance of natural foods was reduced and that of artificial feed was increased when DO was limited. Moreover, b_a became the second most sensitive parameter affecting growth of open-pond tilapia when DO was below the critical limit. Compared with DO, UIA has smaller effects on the growth of both caged and open-pond tilapia. Beyond the critical limit (0.06 mg l^{-1}), UIA slightly reduced the importance of artificial feed for caged tilapia and the importance of natural foods for open-pond tilapia, but slightly increased the importance of artificial feed on open-pond tilapia. UIA did not change the order of sensitivity of the parameters to growth of open-pond tilapia whereas DO did influence the ordering of parameters.

Sensitivity analysis for key variables affecting Nile tilapia growth (Table 2) showed that the growth of caged tilapia was most sensitive to artificial feed availability followed by the stocking size of caged tilapia when DO was not limited, but growth was most sensitive to DO when it was limited. UIA was the third most sensitive parameter affecting growth of caged tilapia when UIA was limited, although the sensitivity (about 0.77 for a 10% change) was low. When both DO and UIA were limiting factors, artificial feed became more important and natural foods less important for growth of open-pond tilapia. However, DO (even below the critical limit) was not the variable most affecting the growth of open-pond tilapia; growth of open-pond tilapia was most sensitive to the amount of artificial feed available to caged tilapia.

Lowering water quality (by decreasing DO or raising UIA 10%, respectively) further reduced the growth of caged tilapia and increased the growth of open-pond tilapia. The growth of open-pond tilapia was more sensitive to variables affecting caged tilapia than the variables affecting their own growth. Growth was least sensitive to water temperature for both caged and open-pond tilapia. When DO and UIA did not reach their critical limits, the growth of neither caged nor open-pond tilapia was affected.

Discussion

The present model was validated using growth data reported by Yi et al. (1996) and Yi (1997) of both caged and open-pond Nile tilapia in 28 ponds from a cage-cum-pond integrated culture system. Compared with previous models for Nile tilapia growth (Liu and Chang, 1992; Nath et al., 1994; Bolte et al., 1995; Yi, submitted), this model incorporated a new parameter, feeding efficiency (q, including q_c and q_p), to describe the physical form and application method of artificial feed and natural nitrogen fixation processes. These modifications may make it possible to simulate the growth of Nile tilapia in culture systems with varying availability of natural foods and/or different types of artificial feed.

Fish growth is affected largely by the nutritional quality and quantity of food. The parameters b and a, efficiency of food assimilation and fraction of the assimilated food used for feeding catabolism, reflected the nutritional quality of different foods. For natural foods, average values of b and a are used for all food resources in ponds. Even though it is relatively convenient to use the unique values of b and a for each type of artificial feed given to fish, it is, nonetheless, difficult to determine complex compositions of such food resources under different culture conditions. High quality feed has a large b value and a small a value. However, fish growth is also affected by physical form and application method of feed, which affect the amount of feed fish are able to consume. These are described by the feeding efficiency parameter in the present model. For floating pellets, q was assumed to be 1 based on its physical form when it was given to tilapia at large in ponds; however, q was 0.95 for tilapia confined in cages because it was assumed that 5% of the feed given was knocked out of cages due to vigorous swimming activity of caged tilapia (Collins, 1971; Coche, 1979; McGinty, 1991; Yi, 1997). For other types of artificial feed, q ranges from 0 to 1. Thus, this parameter allows one to simulate how fish growth is affected in different culture systems receiving different artificial feeds. Jamu and Piedrahita (1996) incorporated a parameter, the coefficient of feed quality, in their model to describe the effects of variable feed quality on fish growth; however, this parameter only accounted for how the nutritional quality of feed affected fish growth, which had been described by other parameters *b* and *a*.

A significantly large amount of nitrogen fixation may occur in Nile tilapia ponds fertilized organically or inorganically (Lin et al., 1988). Even though nitrogen fixation rates fluctuated over a wide range (Lin et al., 1988), the mean rate of nitrogen fixation was used in the present model. The simulated results indicated that nitrogen derived from natural biological fixation was an important source of nitrogen input in ponds, a finding consistent with conclusions made by Lin et al. (1988). Yi (submitted) reported that the simulated growth of Nile tilapia in well-fertilized ponds (4 kg N ha^{-1} day^{-1} and 1 kg P ha^{-1} day^{-1}) was limited as a result of carbon limiting primary production during 55 to 99% of the culture period; however, the present model indicated that carbon was not a limiting nutrient to primary production in the cage-cum-pond integrated culture system fertilized by cage wastes at rates of 0.62 to 2.36 kg N ha^{-1} d^{-1} and 0.12 to 0.53 kg P ha^{-1} d^{-1} (Yi, 1997). Growth of open-pond tilapia was limited due to phosphorus and nitrogen limiting primary production during the entire period of the experiments. This implies that carbon limitation might not occur in fed ponds unless fertilizer is also applied or that organic inputs add carbon to the water. These results suggest that the balance of fertilizer inputs should be evaluated carefully in both fertilized and fed ponds to maintain good water quality, maximize nutrient utilization, reduce nutrient discharge, and minimize production costs.

Simulation of open-pond tilapia growth by the present model explained why Yi (1997) found that open-pond tilapia grew faster when water quality declined (low DO and high UIA) than when water quality was maintained at optimal levels (DO above and UIA below their respective critical limits). Food consumption of caged tilapia was reduced when water quality was depleted. This caused slower growth of caged tilapia and, thus, more uneaten artificial feed, which was then available to the open-pond tilapia. The total food consumption of open-pond tilapia was also reduced; however, tilapia consumed high quality artificial feed instead of lower quality natural food, because Nile tilapia prefer artificial feed to natural foods under culture conditions (Schroeder, 1978). Therefore, instead of observing a reduction in the growth of open-pond tilapia in depleted water quality conditions, an increase in growth was observed to some extent. This also explained why the growth of open-pond tilapia was more sensitive to parameters related to the availability of artificial feed than the parameters related to the availability of natural foods, when water quality declined.

Some modifications might be made to the model once the necessary information is available. For example, further definition of water quality parameters, especially DO, is necessary to determine how food consumption and ultimately the growth of Nile tilapia are affected. Growth is much more sensitive to water quality parameters when they become limiting factors. Parameters related to feed intake and net energy from feeding (q_c, q_p, b_a, b_n, a_a, a_n) are also sensitive to the model output but are not well defined, thus, more research is required. The model also should be reparameterized to simulate growth of other fish species cultured in different environments.

Anticipated Benefits

This study led to the development of a model that successfully simulates the growth of caged tilapia feeding on artificial pelleted feed and open-pond tilapia which depend on the wastes of cage cultured tilapia. This study has indicated that the primary production in ponds fertilized by cage wastes is limited by nitrogen and phosphorus. The results will be useful for our understanding and management of integrated aquaculture systems.

Acknowledgments

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Evaluation of Low Cost Supplemental Diets for Culture of *Oreochromis Niloticus* (L.) in North Vietnam (Part I)—Formulation of Supplemental Diets

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Thailand Special Topics Research 3

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Introduction

With more than 400,000 hectares of inland waters, Vietnam possesses a great potential for freshwater fish culture (Asian Development Bank/FAO, 1992). However, most fish farming systems are extensive polyculture of Chinese carps. In recent years, the growing demand for fish in domestic markets has encouraged Vietnamese fish farmers to intensify pond culture. Many of them now are trying to expand from a grass carp (*Ctenopharyngodon idella*) based polyculture to achieve higher yields with Nile tilapia (*Oreochromis niloticus*) (Ha Noi Extension Center, 1996).

Nile tilapia was imported from Thailand to North Vietnam in 1994. In a few years, this species has quickly gained popularity among most northern fish farmers due to its fast growth and attractive appearance. However, overwintering fish remains a problem in the northern region, often forcing tilapia farmers to harvest their fish before the winter. In this situation, farmers need to achieve fast fish growth within a limited period of cultivation.

Supplemental feeding in fertilized ponds results in faster fish growth and higher pond yields at high stocking density compared to ponds that receive only fertilization (Hepher, 1963; Tacon, 1988). At present few studies of supplemental feeding of Nile tilapia have been conducted in Vietnam. Most farmers use only rice bran for fish feeding and economic returns from this feeding practice still remain questionable. Although studies on this issue have been carried out in some countries (Guerrero, 1980; Middendorn and Verreth, 1991;

Table 1. Formulas and costs of the experimental diets.

Treatment Diet	Formulation	Feed Cost (US$ kg^{-1})
T1	Chicken feed brand C23A (20% protein) produced by Pronconco Company.	0.48
T2	Chicken feed brand C20 (40% protein) mixed with corn meal.	0.35
T3	Chicken feed brand C20 (40% protein) mixed with cassava meal.	0.33
T4	Chicken feed brand C20 (40% protein) mixed with rice bran	0.31
T5	Fish meal brand Kien Giang (50.4% protein) mixed with corn meal.	0.28
T6	Fish meal bran Kien Giang (50.4% protein) mixed with cassava meal.	0.27
T7	Fish meal bran Kien Giang (50.4% protein) mixed with rice bran.	0.26
T8	Corn meal (11.2% protein)	0.02
T9	Rice bran (8.7% protein)	0.19

Green, 1992; Diana et al. 1994), few of them are applicable to Vietnam due to differences in the natural environment and socioeconomic conditions. Economically feasible diets need to be developed in Vietnam using locally-available ingredients such as rice bran, corn meal, cassava meal, fish meal, and chicken feed. The objective of this study was to develop practical supplemental diets for the culture of Nile tilapia in North Vietnam. Part I of this two-paper series focused on the selection of good supplemental diets, and Part II concentrated on determining the economically optimal feeding rate of the selected diet for tilapia raised in fertilized ponds.

Methods and Materials

The experiment was carried out at the Research Institute for Aquaculture No. 1, located approximately 14 km northeast of Hanoi. Cages were constructed of metal frames and 1.5-cm mesh nylon net. Twenty-seven net cages, each 1 x 1 x 1.2 m (W x L x H), were placed 1 m into water, giving a submerged volume of 1 m^3 and suspended 20 cm above the pond bottom. The cages were arranged into three blocks in a 1000-m^2 earthen pond.

Nile tilapia of the Chitralada strain, offspring of the stock imported from Thailand in 1994, were used in this study. Sex-reversed, all male fingerlings (produced at the Research Institute for Aquaculture No.1) with a mean weight of 8.4 g were stocked in cages at a density of 25 fish m^{-3}.

Nine supplemental diets (Table 1) were formulated using locally-available materials of various costs. Feeds were compressed into pellets by a hand-powered extruder. Inorganic fertilizers (urea and superphosphate) purchased from local markets were applied at a rate of 28 kg N and 7 kg P ha^{-1} wk^{-1}. Over a 90-day culture period (April to July 1996) feed was given daily at a rate that decreased with fish growth from 15% to 3% of body weight. Feed ration was placed in feeding trays which were suspended at mid depth in each cage. Rations were adjusted daily for each cage.

Weather data (solar radiation, air temperature, hours of sunshine, rainfall, humidity, and wind speed) were gathered daily by the Ha Noi Meteorological Station nearby. Water temperature and dissolved oxygen (DO) were measured daily at 06:30 h using a Yellow Spring Instrument (YSI) DO meter. DO and temperature were measured at two depths: 15 cm below the water surface and 15 cm above the cage bottom. Secchi disk visibility, chlorophyll *a*, pH, alkalinity, total ammonia, nitrate, nitrite, orthophosphate, total phosphorus, and solids were measured weekly. Visibility was calculated as the average depth at which the Secchi disk disappeared when lowered, and the depth at which it reappeared when raised (Boyd and Tucker, 1992). Chlorophyll *a* was analyzed using spectrophotometric method (APHA, 1980). Alkalinity and concentrations of total ammonia, nitrate, nitrite, orthophosphate, and total phosphorus in water were determined using standard methods (APHA, 1980): alkalinity was determined by titration with H_2SO_4 (0.02 N); total ammonia was measured by phenate method, nitrate was measured by cadmium reduction method, nitrite was measured by colorimetric method using diazotizing reagents, orthophosphate was measured by ascorbic acid reduction method, and total phosphorus was measured by persulfate digestion method (APHA, 1980). Proximate analyses of harvested fish carcass were completed according to the AOAC (1990).

To obtain survival and fish growth data the stock of each cage was counted and weighed every two weeks beginning with the initial stocking. Daily weight gain (DWG) was calculated using the following formula: DWG (g $fish^{-1}$ day^{-1}) = (final weight - initial weight)/number of days in culture period. Feed conversion ratio (FCR) was calculated as feed given per kilogram of wet weight gain.

Analysis of variance (ANOVA) was used to determine differences between treatments in mean final weight, production, daily weight gain, feed conversion ratio, survival rate, and protein content of carcasses of harvested fish. Duncan's multiple range test was used for screening the best treatments (Gomez and Gomez, 1984). A simple economic comparison was made to identify the most cost-effective diet.

Results

Climate

The study site, located in the Red River delta of Vietnam, has a subtropical climate which is dry and cool in the winter and moist and hot in the summer (The Fisheries Master Plan Project, 1996). During the experimental period (from late April to late July 1996) solar radiation, sunshine, and air temperature gradually increased and peaked in week 6 (mid June). The average solar radiation over the experimental period was 7,157 W m^{-2} d^{-1}, sunshine was 4.4 hours d^{-1}, and temperature was 28.3°C. Rainfall also increased and was heaviest in the last two months of the experiment (June-July). Over the experimental period, the average rainfall was 37.5 mm wk^{-1}, evaporation rate was 2.9 mm d^{-1}, humidity was 78.2%, and wind speed was 2.4 m s^{-1}.

Water Quality Parameters

There were no significant differences in water quality parameters between treatments ($P > 0.05$). Similar to air temperature, water temperature also gradually increased over time, from 20°C in the first week to 28 to 33°C for the remaining experimental period. The mean water temperature over the experimental period was 29.2°C. Secchi disk depth decreased gradually with time, ranging from 20 to 40 cm. Water pH was relatively stable, ranging from 6.9 to 8.3. Early morning dissolved oxygen (DO) ranged from 2 to 3 mg l^{-1} in the first 9 weeks and decreased to 0.5 to 1.0 mg l^{-1} in the last 3 weeks. Alkalinity decreased slightly over time, ranging from 76 to 117 mg $CaCO_3$ l^{-1}. Total ammonia concentration significantly increased, beginning with week 7, and ranged from 0.19 to 0.5 mg l^{-1} over the whole period. Nitrite concentration ranged from 0.001 to 0.02 mg l^{-1} with the exception of week 8 when it reached 0.05 mg l^{-1}. Nitrate concentration ranged from 0 to 0.8 mg l^{-1}; orthophosphate concentration ranged from 0.013 to 0.2 mg l^{-1}; total phosphorus ranged from 0.1 to 0.4 mg l^{-1}; chlorophyll *a* concentration ranged from 97 to 200 mg m^{-3}; total solids ranged from 100 to 400 mg l^{-1}; total dissolved solids ranged from 90 to 320 mg l^{-1}; total suspended solids ranged from 12 to 70 mg l^{-1}; total volatile dissolved solids from 33 to 255 mg l^{-1}; and non-filterable volatile solids ranged from 9 to 33 mg l^{-1}.

Fish Growth Performance and Economic Comparison

There were significant differences among the experimental diets in fish growth rate and production ($P < 0.01$), but not in survival rate nor crude protein content of carcasses of harvested fish ($P > 0.05$) (Figure 1 and Table 2). During the 90-day culture period the diet containing 20% crude protein formulated from concentrated chicken feed (40% crude protein) and cassava meal (T3) resulted in the fastest growth of tilapia (mean individual weight at harvest of 180.2 g and daily weight gain of 1.91 g) followed by the diet of chicken feed brand C23A, containing 20% crude protein (T1) (mean individual weight at harvest of 170.4 g and daily weight gain of 1.82 g). These two diets also resulted in the highest fish production and lowest feed conversion ratios. The treatments with diets formulated from fish meal and cassava meal (T6), from fish meal and corn meal (T5), and from chicken concentrated feed and rice bran (T4) gave intermediate fish growth rates and yields. Corn meal (T8) and rice bran (T9) produced the slowest fish growth and highest FCRs.

An economic comparison showed that the diet formulated from concentrated chicken feed and cassava meal (T3) had the highest net profit and returns to investment (Figures 2 and 3). This diet had relatively high feed investment per unit of cultured area but the lowest break even price

Table 2. Comparison of fish growth performance in response to various experimental diets over a 90-day culture period.

Treatments	Stocking Weight (g fish^{-1})	Harvesting Weight (g fish^{-1})	Daily Weight Gain (g fish^{-1} d^{-1})	Fish Production (kg m^{-3})	Feed Conversion Ratio
T1	8.4^{a}	172.4^{ab}	1.82^{ab}	4.04^{ab}	1.63^{ab}
T2	8.4^{a}	158.2^{bc}	1.66^{bc}	3.65^{ab}	1.77^{ab}
T3	8.4^{a}	180.2^{a}	1.91^{a}	4.17^{a}	1.64^{a}
T4	8.4^{a}	150.1^{c}	1.57^{c}	3.40^{abc}	1.81^{ab}
T5	8.4^{a}	141.9^{c}	1.48^{c}	3.34^{abc}	1.94^{ab}
T6	8.4^{a}	137.1^{c}	1.43^{c}	3.13^{bcd}	1.83^{ab}
T7	8.4^{a}	138.0^{c}	1.44^{c}	2.59^{cd}	2.92^{d}
T8	8.4^{a}	100.8^{d}	1.03^{d}	2.25^{d}	2.55^{bc}
T9	8.4^{a}	106.4^{d}	1.09^{d}	2.27^{d}	2.56^{bc}

^{abcd} Treatments annotated with the same superscript are not significantly different ($P > 0.05$)

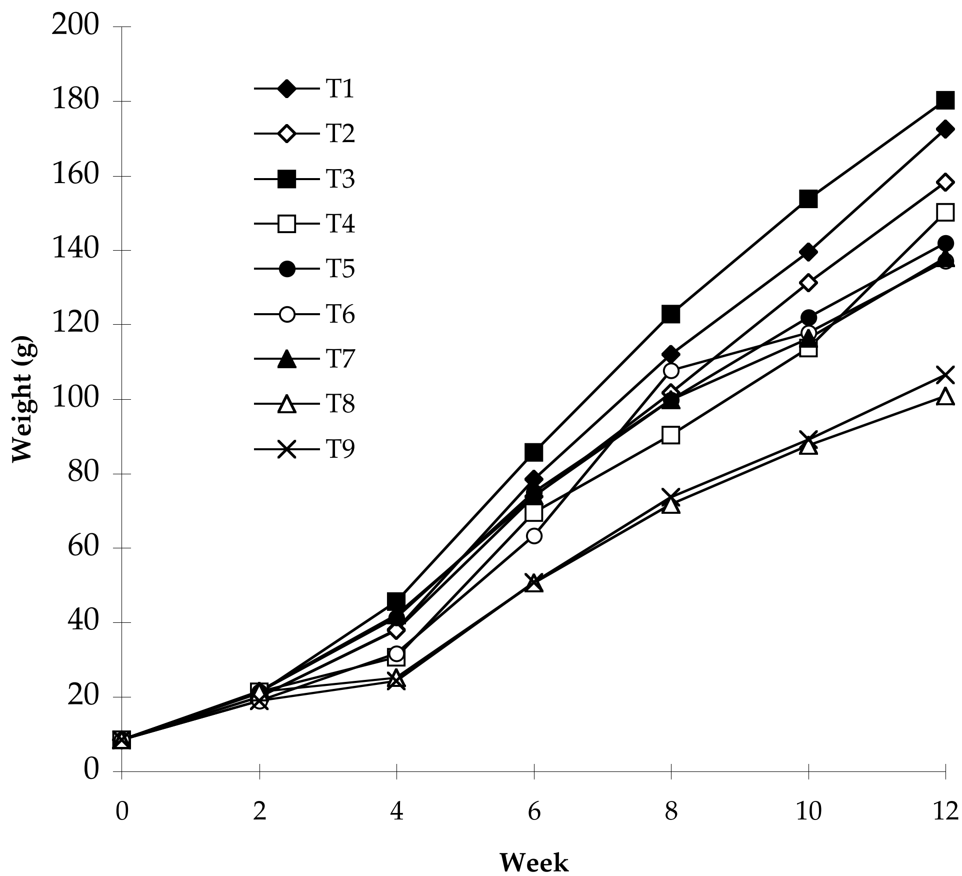

Figure 1. Fish growth curves in response to various experimental diets over a 90-day culture period.

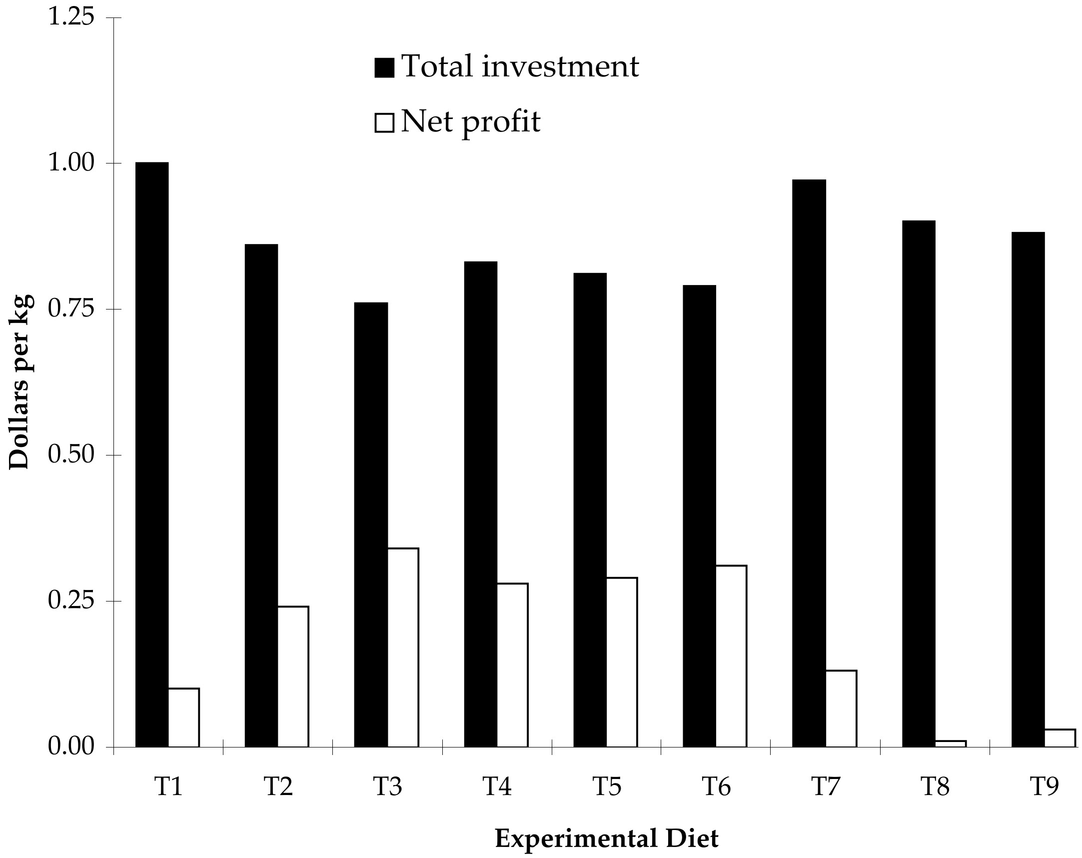

Figure 2. Comparison of net profit and total investment per kg of fish produced among the experimental diets.

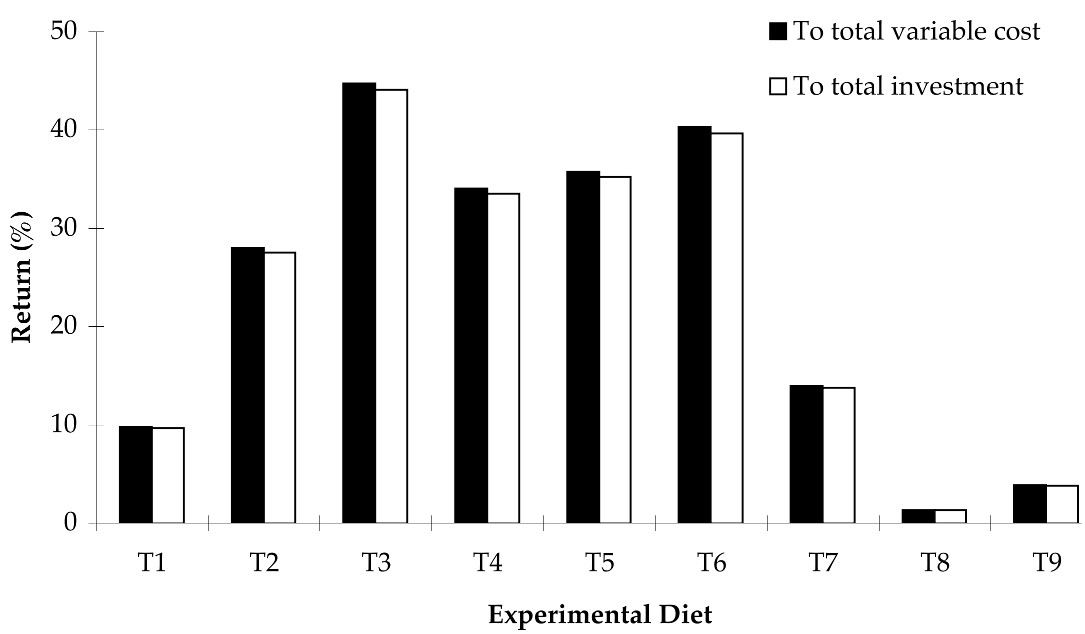

Figure 3. Comparison of returns to variable cost and to total investment among the experimental diets.

Table 3. Simple economic comparisons among the experimental diets for a 1 m^3 cage.

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Harvest									
Biomass Harvested (kg)	4.25	3.85	4.38	3.60	3.55	3.33	2.75	2.46	2.47
Unit Price ($ kg^{-1})[a]	1.10	1.10	1.10	1.10	1.10	1.10	1.10	0.91	0.91
Total Revenue ($)	4.68	4.24	4.82	3.96	3.91	3.66	3.03	2.24	2.25
Variable Costs[b]									
Fish Seed ($)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Feed ($)	3.17	2.24	2.26	1.89	1.81	1.55	1.59	1.15	1.10
Urea ($)	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Superphosphate ($)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Lime ($)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total Variable Costs ($)	4.20	3.27	3.30	2.92	2.85	2.58	2.62	2.18	2.13
Interest ($)	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03
Total Cost per 1 m^3 Cage ($)	4.26	3.32	3.34	2.97	2.89	2.62	2.66	2.21	2.17
Gross Margin per m^3 Cage ($)	0.48	0.96	1.52	1.04	1.06	1.08	0.40	0.06	0.11
Net Profit per 1 m^3 Cage ($)	0.41	0.91	1.47	0.99	1.02	1.04	0.37	0.03	0.08
Total Investment per 1 kg Fish ($ kg^{-1})	1.00	0.86	0.76	0.83	0.81	0.79	0.97	0.90	0.88
Net Profit per 1 kg Fish ($ kg^{-1})	0.10	0.24	0.34	0.28	0.29	0.31	0.13	0.01	0.03
Return to Total Variable Cost (%)	9.80	27.95	44.71	34.00	35.72	40.26	13.96	1.31	3.86
Return to Total Investment (%)	9.68	27.54	44.05	33.50	35.19	39.66	13.75	1.29	3.80

[a] The prices for fish larger and smaller than 110 g were US$ 1.10 and US$ 0.9 kg^{-1}, respectively.
[b] For the experimental scale (a few small cages), labor cost was not included in the analysis.

(total investment per kg of fish produced) due to its high production. The diet formulated from fish meal and cassava meal (T6) had the second highest net profit followed by the diets derived from fish meal and corn meal (T5) and from concentrated chicken feed and rice bran (T4). Compared to the other diets chicken feed brand C23A (T1) had high fish production but low net profit due to its high feed cost. Treatments of corn meal (T8) or rice bran (T9) alone yielded the lowest profits and returns to investment. Although these two treatments were the least expensive, their break even prices were very high due to low fish production.

An overall comparison indicated that the diet containing 20% crude protein derived from concentrated chicken feed (40% crude protein) and cassava meal (T3) was the most economical for tilapia farming in North Vietnam, followed by the diets derived from fish meal and cassava meal (T6), from fish meal and corn meal (T5), and from concentrated chicken feed and rice bran (T4).

Discussion

Nile Tilapia is considered a prime species for culture in tropical and subtropical regions, because it has a fast growth rate and adapts to a wide range of environmental conditions. In the present study, climatic and water quality parameters varied within acceptable ranges for normal growth of tilapia. Differences in water quality parameters between treatments were not significant ($P > 0.05$) implying that all experimental diets were environmentally suitable for tilapia culture.

Tilapia feed on a large variety of natural food organisms found in fertilized ponds (Yashouv and Chervinski, 1961; Bowen, 1982; Trewavas, 1983); however, their growth rate decreases once the critical standing crop in fertilized ponds has been attained, because the quantity of natural food can no longer support rapid growth (Tacon, 1988). Supplemental feeding at this time permits fish to continue to grow rapidly (Hepher, 1978). In North Vietnam where a long, cold winter prevails and culture periods are shorter, the use of supplemental feed is required to improve the harvest size of tilapia. However, feed is often 60% or more of total production cost so that feed cost reductions can substantially increase the profitability of a culture system. In Thailand chicken pellets (19.9% crude protein) were experimentally determined to be a suitable supplemental feed for the cage culture (Chiayvareesajja et al., 1988). During a five-month culture period Nile tilapia increased from an initial weight of 13.5 g to a final weight of 108.7 g with a yield of 3.43 kg m^{-3}. In the Philippines, Guerrero (1980) indicated that diets with 25% fishmeal and 75% fine rice bran or 25% fishmeal, 10% copra meal, and 65% rice bran were economical for cage culture of Nile tilapia.

In the present study the diet containing 20% crude protein formulated from concentrated chicken feed (40% crude protein) and cassava meal (T3) was found to give the best growth of Nile tilapia. The data in Table 2 shows a trend indicating that all treatment diets using concentrated chicken feed as a main source of protein resulted in faster growth rates and higher production than the treatment diets using fish meal; however, the differences were not statistically significant ($P > 0.05$). This trend may be due to micronutrients that have been added to concentrated chicken feeds by producers. Table 2 data also indicates that all diets containing rice bran have slower growth rates and lower production than the diets containing cassava or corn meals. This finding may be related to the quality of rice bran purchased in local markets. Large amounts of rice bran sold in Ha Noi were imported from the Southern region (the Mekong delta). Fish kills observed locally may be attributable to feeding rice bran that may have spoiled during lengthy transportation from the south, or during storage under conditions of high humidity in the north.

Economic comparison of treatments (Table 3) favored the utilization of formulated feeds for Nile tilapia culture rather than single-ingredient feeds, (i.e., corn meal or rice bran) that are widely used in Vietnam. Rice bran or corn meal alone resulted not only in low production and profit but also in a high break even price. Results from this study indicate that using the appropriate formulated diets as supplemental feed for Nile tilapia in fertilized ponds is profitable in North Vietnam. In the present study the highest profit (US$ 0.34 kg^{-1} fish) was achieved when fish were fed a 20% crude protein diet derived from concentrated chicken feed (40% crude protein) and cassava meal (T3). This diet had the lowest break-even price but required a relatively high total feed investment per unit of area cultured. The diets formulated from fish meal and cassava meal (T6), fish meal and corn meal (T5), and concentrated chicken feed and rice bran (T4) were suggested as viable alternatives for farmers who require feeds with lower investment costs but relatively high net profits and returns.

Anticipated Benefits

The use of supplemental feeds to facilitate faster tilapia growth under colder climates is a major production practice in Vietnam. This study provides evidence that supports the use of locally available waste products and feed materials in tilapia production rather than the use of remotely prepared feeds which are expensive to use and difficult to transport. As such, this study has immediate usefulness in the profitability of tilapia culture locally. The results of this study will be widely tested by aquaculturists and extension personnel to improve grow out conditions and profitability. It will also lead to further experimentation on feed development and efficient feeding systems. Such experimentation and extension will likely enhance the economic returns to tilapia farmers.

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Development of Low Cost Supplemental Feeds for Tilapia in Pond and Cage Culture in the Philippines

Eighth Work Plan, Philippines Research 1 (PHR1)

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Introduction

Supplemental feeds providing additional quantities of nutrients are needed when the productivity of a water body cannot provide sufficient nutrients to achieve the desired fish growth. Low cost but good quality feeds are needed when farmers wish to produce more fish than can be supported by fertilized systems (Diana et al., 1996) and in instances when fish are cage cultured and do not have access to the entire water body for feeding. Many small-scale farmers have been encouraged to build and utilize cages to increase their household income and nutrition. After construction of the cage, cost of feed becomes the major input cost for fish production.

Supplemental feeds, by definition, are not intended to provide complete nutrition. The goal is to provide nutrients that otherwise would be limiting to fish growth. In fertilized ponds, proteins are often that limiting factor. Dietary protein is often expensive to incorporate in a diet; however, the provision of protein in feeds may be cost-effective if the growth rate of stocked fish is increased and if protein provision in feed allows for increased numbers of fish to be stocked in the same water volume. The typical sources of proteins are fish meal and soy bean oil meal, which are relatively expensive ingredients that are useful in other animal feeds. Determining less expensive sources of protein has been a goal of previous nutrition studies, which have examined many ingredients from plants, agricultural processing wastes, and even brewery wastes. One source of protein that was historically prohibitively expensive is yeast; however, new bioreactor technology has lowered the cost of yeast to the point that it may now be cost-effective to use as an ingredient. Brewers' and bakers' yeasts are known to be high in protein and readily digestible. One common yeast used in feed studies that is commercially available in many areas is *Saccharomyces cereviseae.*

Rice bran is an agricultural by-product that has been used in supplemental diets in the past. Another material available from rice production is rice straw; however, the straw is not high in protein. Composting is a solution that addresses this problem. Microbes convert the straw from a material high in indigestible matter to microbial biomass that is quite digestible for tilapia.

The current study will examine the potential for using yeast and composted rice straw as ingredients in supplemental tilapia feeds. A secondary aspect of this study will assess the use of compression pelleting technology to form these feeds. Compressed pellets are a technological improvement over diets formed from meat grinding equipment, because the pellet has better stability in water. Fish have a better opportunity to ingest and digest pelleted food.

Methods and Materials

The trials will be conducted in two parts. In Phase 1, fish will be fed the experimental diets as a supplemental feed in conventional ponds with four ponds per treatment. In Phase 2, fish will be

Table 1. Water parameters were analyzed (APHA, 1980; Boyd, 1979) at initial stocking and every two weeks thereafter.

Parameter	Depth	Time	Analytical Methods
Temperature	Top, mid, bottom	AM and PM	YSI meter and probe
Dissolved O_2	Top, mid, bottom	AM and PM	YSI meter and probe
Alkalinity	Column sample	AM	Titration
pH	Top, mid, bottom	AM and PM	pH meter
Total NH_3-N	Column sample	AM	Indophenol method
Soluble Reactive Phosphorus	Column sample	AM	Molybdate method

stocked in cages placed in the same pond and fed the experimental diets, with four cages per treatment.

Phase 1

Ponds at the Freshwater Aquaculture Center (FAC) at Central Luzon State University (CLSU) are being used to test the experimental diets. On 10 June 1997 we stocked 12 earthen ponds with monosex (genetically male) *Oreochromis niloticus*, purchased from the Fish-Gen Project at CLSU, at a density of three fingerlings m^{-2} (1,500 fish $pond^{-1}$). Each pond has an area of 500 m^2 (25 m x 20 m) and a depth of approximately 1 m.

Each of the 12 ponds receives nutrient inputs from urea (46-0-0) and ammonium phosphate (16-20-0) at the rate of 14 kg N and 2.8 kg P ha^{-1} wk^{-1}, respectively. To attain these levels, 1.625 kg of 16-20-0 and 1.1 kg of urea ammonium phosphate (45-0-0) were added weekly to each 500 m^2 pond. To calculate fertilizer input we assumed a moisture content of approximately 5% in the fertilizer. Dissolved fertilizer was broadcast across the entire pond surface. Nutrient application will be discontinued once feeding begins in all ponds receiving feeds (experimental ponds) and will continue in ponds receiving only fertilizers (control ponds). Feeding with the experimental diets will be at 5% BWD for two months and 3% BWD during the last month until harvest.

Commercially-available yeast will be used to produce one of the experimental diets (60% rice bran, 15% yeast, 25% meat and bone meal) composted rice straw (60% rice bran, 15% rice straw, 25% meat and bone meal) will be used to produce the other experimental diet. Two batches of rice straw compost were prepared—the first in January 1997 and the second in June 1997. Compost preparation did not involve any nutrient supplementation nor manure additions. The diets will be prepared on a meat grinder for the first trial. A compression-style pelleting mill (CPM Master Series) will be used for future trials.

Body weight and length data were collected at the initial stocking of ponds. Fifty samples per pond were taken. Fish body weight will be determined on a monthly basis by bulk weighing at least 100 individuals per pond and at harvest complete (i.e., 100% of all fish) bulk weights and counts will be made. At the initiation of feeding, fish will be sampled every two weeks in ponds receiving feed, so that feed rations may be adjusted.

The ponds have been allocated randomly to the two pelleted feed treatments (yeast and rice straw compost) and a fertilized pond control treatment. The experimental diets are scheduled to begin on 1 September 1997.

Phase 2

Twenty units of 6-m^3 cages will accommodate a two x two factorial experiment (feed preparation by pellet mill or meat grinder, and compost or yeast-based diets) with five replicates. The pond where the net cages will be installed has an area of 2,500 m^2 and a depth of 1.5 to 2 m. The cages will be stocked with GIFT *Oreochromis niloticus*, sex-reversed by treatment of fry with methyltestosterone feed as per standard FAC protocols.

Table 1 summarizes the water quality parameters measured and the equipment used for measurement.

For Phases 1 and 2, the hypothesis that fish growth will be similar between treatments will be tested with ANOVA. The tests will be performed with

Table 2. Initial, 30-, and 60-day post stocking weights (g).

Treatment	Pond	Day 0	Day 30	Day 60
YEAST				
	5E	0.5	21.9	48.0
	5B	0.5	15.9	36.0
	6A	3.4	9.7	16.3
	6E	3.1	35.2	86.0
	Average	1.9	18.3	46.6
COMPOST				
	6H	2.0	21.1	57.0
	6F	2.4	31.0	71.0
	5C	0.7	17.9	33.0
	5F	0.8	23.3	54.0
	Average	1.5	23.3	53.75
FERTILIZER ONLY				
	5J	1.8	33.9	80.0
	6D	2.8	35.4	83.8
	4H	0.6	21.2	48.6
	4J	0.5	22.4	51.0
	Average	1.4	28.2	65.8

the assistance of SAS, SYSTAT, or a comparable software package.

Breeding, fry collection, and hormone treatment were carried out from March through April 1997. The hormone-treated fry were nursed during the whole month of May and were stocked in ponds at three fish m^{-2} on June 10.

Results

As of September 1997 fish growth is solely dependent on the algal productivity of the ponds.

Table 2 summarizes the results of the initial, and 30- and 60-day post stocking weights. Table 3a displays water quality data (dissolved oxygen, temperature, and pH); table 3b displays water quality data (Secchi disk visibility [SDV], alkalinity, total available nitrogen [TAN] and phosphorus [P]).

Anticipated Benefits

The suitability of two locally-available sources of protein will be determined, in the anticipation that yeast and composted rice straw can be used to provide an additional protein element in supplemental fish feed. This will reduce feed costs compared with currently-used fish meal protein sources. This research will also determine the relative efficiencies of two modes of feed preparation, a meat grinder or a pellet mill.

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Table 3a. Results of initial water sampling (average of each parameter).

Sample #	Treatment	Pond	Dissolved Oxygen (mg l^{-1})		Temperature (°C)		pH	
			AM	*PM*	*AM*	*PM*	*AM*	*PM*
#0								
	Yeast	5E	1.83	10.37	30	33.9	7.2	7.8
		5B	4.53	11.5	30	35.2	7.6	8.1
		6A	4.23	10.67	31.2	35	6.7	6.3
		6E	4.17	10.17	30.2	34.1	7.3	7.1
		Average	3.69	10.68	30.4	34.5	7.2	7.3
	Compost	6H	3.4	7.17	30.5	34.4	6.9	7.7
		6F	0.57	8.93	29.2	34	7.4	7.6
		5C	4.43	12.63	29.7	34.4	7.5	8.1
		5F	0.43	7.07	29.8	33.9	7.1	7.5
		Average	2.21	8.95	29.8	34.2	7.2	7.7
	Fertilizer	5J	0.7	8.6	29.5	34.6	7.3	8
		6D	0.77	6.67	29.5	34.5	7.2	6.9
		4H	0.43	1.63	29	33.3	7.6	7.9
		4J	1.93	10.97	30	34.1	7.6	7.6
		Average	0.96	6.97	29.5	34.1	7.4	7.6
#1								
	Yeast	5E	2.37	5.1	29.5	30.5	7.4	7.8
		5B	3.43	7.13	29.1	30.1	6.5	6.8
		6A	4.9	5.9	30.1	30.7	7.7	8.1
		6E	2	7.2	29.3	30.2	7.9	8.7
		Average	3.18	6.33	29.5	30.4	7.4	7.9
	Compost	6H	4.6	12.1	29.3	30.3	8.1	9.1
		6F	0.6	2.7	29.5	30.4	7.9	8.7
		5C	3.8	7.63	29	30.2	7	7.5
		5F	1.43	4.13	29.7	30.6	7.4	7.9
		Average	2.61	6.64	29.4	30.4	7.6	8.3
	Fertilizer	5J	0.7	3.7	29.2	30.6	8.1	9
		6D	1.9	6.6	29.3	30.1	7.8	8.5
		4H	0.33	4.33	28.9	30.2	7.4	7.9
		4J	0.3	3.77	29.5	30.8	7.5	7.9
		Average	0.81	4.6	29.2	30.4	7.7	8.3

Table 3a. Continued.

Sample #	Treatment	Pond	Dissolved Oxygen (mg l^{-1})		Temperature (°C)		pH	
			AM	*PM*	*AM*	*PM*	*AM*	*PM*
#2								
	Yeast	5E	4.3	14.27	29.8	33.7	9.5	9
		5B	5.03	15.2	29.1	15.2	8.4	9
		6A	6	9.7	30.3	33.2	7.5	7.8
		6E	3.2	14.3	29.9	33.7	7.8	8.4
		Average	4.63	13.37	29.8	29	8.3	8.6
	Compost	6H	0.7	10.5	29.6	33.4	8.2	8.7
		6F	0.7	12.6	29.8	34.1	7.8	8.4
		5C	5.07	16.63	29	16.6	9.5	9
		5F	2.63	8.9	30	34.1	8.7	8.8
		Average	2.28	12.16	29.6	29.6	8.5	8.7
	Fertilizer	5J	1.4	12.4	30	34.5	8.2	8.8
		6D	1.6	14.3	29.6	33.6	7.6	8.2
		4H	0.67	10.63	29.6	34.2	8.4	8.7
		4J	1.2	15.03	29.9	34.4	8.3	8.7
		Average	1.22	13.09	29.8	34.2	8.1	8.6
#3								
	Yeast	5E Yeast	3.27	8.63	27.2	30	7.8	9.1
		5B Yeast	3	7.43	27.2	30.1	7.6	8.9
		6A Yeast	4.7	8.8	27.8	30.1	6.9	7.9
		6E Yeast	2.7	11	27.3	30.8	7.9	9.2
		Average	3.42	8.97	27.4	30.3	7.6	8.8
	Compost	6H Compost	2.5	8.9	27.2	30.5	7.7	9.1
		6F Compost	1.3	8.9	27.4	30.9	7.5	8.6
		5C Compost	3.57	9.17	27.2	30.1	8	9.2
		5F Compost	2.87	8	27.5	30.1	7.5	8.7
		Average	2.56	8.74	27.3	30.4	7.7	8.9
	Fertilizer	5J Fert	2.3	8.1	27.2	30.7	7.3	9.2
		6D Fert	2.4	12.6	27.2	30.9	7.6	9
		4H Fert	0.87	6.67	27.2	30.3	7.2	8.2
		4J Fert	1.23	10.4	27.2	30.5	7.4	9.3
		Average	1.7	9.44	27.2	30.6	7.4	8.9

Table 3b. Results of intial water sampling (average of each parameter).

Sample #	Treatment	Pond	SDV AM	SDV PM	Alkalinity	TAN (ppm)	P (ppm)
#0							
	Yeast	5E	51	59	289	0	0.34
		5B	51	46	298	0	0.54
		6A	58	67	270	0.02	0.43
		6E	66	63	236	0.04	0.15
		Average	56	59	273	0.01	0.36
	Compost	6H	63	53	272	0.03	0.09
		6F	50	50	275	0.05	0.28
		5C	32	32	263	0.02	0.47
		5F	58	54	304	0	0.43
		Average	51	47	279	0.02	0.32
	Fertilizer	5J	44	60	304	0.01	0.64
		6D	63	65	288	0.02	0.5
		4H	62	50	279	0.02	0.17
		4J	65	67	279	0	0.5
		Average	59	61	288	0.01	0.45
#1							
	Yeast	5E	45	39	203	0.01	0.4
		5B	21	26	184	0.01	0.1
		6A	79	66	182	0.01	0.34
		6E	36	35	177	0.01	0.31
		Average	45	42	187	0.01	0.29
	Compost	6H	33	34	182	0.02	0.19
		6F	63	63	217	0.02	0.24
		5C	19	22	159	0.1	0.35
		5F	55	53	220	0	0.57
		Average	43	43	195	0.04	0.34
	Fertilizer	5J	43	43	162	0.01	0.66
		6D	41	41	187	0.01	0.23
		4H	46	47	221	0	0.3
		4J	49	29	214	0	0.58
		Average	45	40	196	0.01	0.44

Table 3b. Continued.

Sample #	Treatment	Pond	SDV AM	SDV PM	Alkalinity	TAN (ppm)	P (ppm)
#2							
	Yeast	5E	29	28	202	0.01	0.54
		5B	23	14	176	0.03	0.08
		6A	69	51	193	0.05	0.27
		6E	41	38	183	0.03	0.25
		Average	40	33	189	0.03	0.28
	Compost	6H	42	41	170	0.05	0.52
		6F	35	33	237	0.06	0.18
		5C	19	18	160	0.05	0.35
		5F	50	49	227	0	0.57
		Average	37	35	199	0.04	0.4
	Fertilizer	5J	29	26	155	0.01	0.37
		6D	56	37	226	0.02	0.34
		4H	35	45	213	0.02	0.18
		4J	31	28	228	0.04	0.23
		Average	38	34	206	0.02	0.28
#3							
		5E	27	26	162	0.11	0.27
	Yeast	5B	25	31	142	0.13	0.07
		6A	86	89	120	0.07	0.18
		6E	34	26	192	0.09	0.21
		Average	43	43	154	0.1	0.18
	Compost	6H	44	43	133	0.1	0.35
		6F	37	37	187	0.07	0.18
		5C	24	21	152	0.13	0.34
		5F	36	33	190	0.06	0.45
		Average	35	34	166	0.09	0.33
	Fertilizer	5J	21	24	135	0.12	0.2
		6D	30	31	270	0.08	0.48
		4H	34	30	187	0.08	0.13
		4J	27	21	177	0.17	0.32
		Average	28	27	192	0.11	0.28

APPENDIX A. ACRONYMS

AIT	Asian Institute of Technology
ANDAH	Asociacion Nacional de Acuicultores de Honduras or Honduran National Association of Aquaculturists
ANOVA	analysis of variance
AOAC	Association of Official Analytical Chemists
BOD	biological oxygen demand
BWD	body weight per day
C	carbon
CFB	critical fish biomass
CLSU	Central Luzon State University
CM	chicken manure
CRSP	Collaborative Research Support Program
DAP	diammonium phosphate
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DM	dry matter
DO	dissolved oxygen
dpf	days post-fertilization
DWG	daily weight gain
ETOH	ethanol vehicle
FAC	Freshwater Aquaculture Center
FAO	Food and Agriculture Organization
FCR	feed conversion ratio
FPX	Federacion de Agroexportadores de Honduras
GA	genetic algorithm
GIFT	genetic improvement of farmed tilapia
GIS	Geographical Information System

GPP	gross primary productivity
ICLARM	International Center for Living Aquatic Resources Management
IIAP	Instituto de Investigaciones de la Amazonia Peruana
K	potassium
MDHT	17α-methyldihydrotestosterone
MT	17α-methytestosterone
N	nitrogen
NFY	net fish yield
OSU-DAST	Oregon State University-Data Analysis and Synthesis Team
P	phosphorus
PD/A CRSP	Pond Dynamics/Aquaculture Collaborative Research Support Program
PL	post-larval
PNPP	potential net primary productivity
ppm	parts per million
ppt	parts per thouand
SD	standard deviation
SDV	Secchi disk visibility
SE	standard error
SRP	soluble reactive phosphorus
TAN	total available nitrogen
TBA	trenbolone acetate
TSP	triple superphosphate
TSS	total suspended solids
TVS	total volatile solids
UC	University of California
UIA	unionized ammonia
UV	ultraviolet
YSI	Yellow Spring Instrument

Appendix B. 15th Annual Administrative Report Contents