ECONOMICS OF BETTER MANAGEMENT PRACTICES FOR SEMI-INTENSIVE SHRIMP FARMS IN HONDURAS AND SHRIMP COOPERATIVES IN NICARAGUA

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Preparation of this document

The research reported in this paper was prepared under the World Bank/NACA/WWF/FAO Consortium Program on Shrimp Farming and the Environment. Due to the strong interest globally in shrimp farming and issues that have arisen from its development, the consortium program was initiated to analyze and share experiences on the better management of shrimp aquaculture in coastal areas. It is based on the recommendations of the FAO Bangkok Technical Consultation on Policies for Sustainable Shrimp Culture[1], a World Bank review on Shrimp Farming and the Environment[2], and an April 1999 meeting on shrimp management practices hosted by NACA and WWF in Bangkok, Thailand. The objectives of the consortium program are: (a) Generate a better understanding of key issues involved in sustainable shrimp aquaculture; (b) Encourage a debate and discussion around these issues that leads to consensus among stakeholders regarding key issues; (c) Identify better management strategies for sustainable shrimp aquaculture; (d) Evaluate the cost for adoption of such strategies as well as other potential barriers to their adoption; (e) Create a framework to review and evaluate successes and failures in sustainable shrimp aquaculture which can inform policy debate on management strategies for sustainable shrimp aquaculture; and (f) Identify future development activities and assistance required for the implementation of better management strategies that would support the development of a more sustainable shrimp culture industry. This paper represents one of the case studies from the Consortium Program.

The program was initiated in August 1999 and comprises complementary case studies on different aspects of shrimp aquaculture. The case studies provide wide geographical coverage of major shrimp producing countries in Asia and Latin America, as well as Africa, and studies and reviews of a global nature. The subject matter is broad, from farm level management practice, poverty issues, integration of shrimp aquaculture into coastal area management, shrimp health management and policy and legal issues. The case studies together provide an unique and important insight into the global status of shrimp aquaculture and management practices. The reports from the Consortium Program are available as web versions (http://www.enaca.org/shrimp) or in a limited number of hard copies.

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[1] FAO. 1998. Report of the Bangkok FAO Technical Consultation on Policies for Sustainable Shrimp Culture. Bangkok, Thailand, 8-11 December 1997. FAO Fisheries Report No. 572. Rome. 31p.

[2] World Bank. 1998. Report on Shrimp Farming and the Environment – Can Shrimp Farming be Undertaken Sustainability? A Discussion Paper designed to assist in the development of Sustainable Shrimp Aquaculture. World Bank. Draft. Available for download at www.enaca.org/shrimp

Abstract

The shrimp farming industry in Central America has experienced remarkable growth over the last two decades and has become one of the leading generators of foreign exchange in countries such as Honduras. Along with development, however, has come recent criticism on potential environmental and social externalities associated with this activity. To address these concerns, several stakeholder groups have formulated and recommended the implementation of Better Management Practices (BMPs), which are directed at improving production efficiency and/or ameliorating potential impacts on the environment. In this study, an economic optimization model with an environmental component was used to evaluate the effects of five specific BMPs on the profitability, optimal selection of management strategies, and net quantities of nutrients discharged by semi-intensive shrimp farms in Honduras and small-scale operations in Honduras and Nicaragua. The BMPs analyzed were: 1) reduction of water exchange rates from 10 to 5%; 2) reduction of production levels to meet pre-determined nutrient discharge limits; 3) distribution of feed through feed trays; 4) sedimentation of the last 10% of drainage effluents in excavated basins; and 5) partial recirculation of effluents through a mangrove biofilter. Results indicated that the BMPs targeted at improving production efficiency (reductions in water exchange rates and feed trays) had the largest potential to reduce net discharges of nutrients; in addition, these BMPs increased profit margins of operations. Integrated mangrove-shrimp pond systems represent a novel and promising approach to treatment of effluents, but more research is needed to estimate true removal capabilities of these system as well as cost requirements.

Content

Abbreviations and Acronyms

BMP	Better Management Practices
BOD_5	5-day Biological Oxygen Demand
COD	Chemical Oxygen Demand
DIN	Dissolved Inorganic Nitrogen
DO	Dissolved Oxygen
FAO	Food and Agriculture Organization of the United Nations
FCR	Feed Conversion Ratio
Ha	Hectare
Kg	Kilogram
LP	Linear Programming
N	Nitrogen
NACA	Network of Aquaculturecentres in Asia-Pacific
PL	Post Larvae
SRP	Soluble Reactive Phosphorus
TAN	Total Ammonia Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TSV	Taura Syndrome Virus
WB	World Bank
WSSV	White Spot Syndrome Virus
WWF	World Wildlife Fund

Introduction

Constant advances in the technology of shrimp aquaculture over the last two decades, coupled with stagnant or declining landings of wild-caught shrimp, have contributed to the emergence of the shrimp farming industry as a significant supplier of shrimp to the world market. Moreover, the shrimp farming industry has developed into an essential economic activity in several Southeast Asian and Latin American countries. In spite of its essential role in the world seafood supply, the industry has recently come under criticism by environmental organizations, which have alleged that untreated farm effluents, destruction of mangroves during pond construction, excessive by-catch associated with the gathering of wild post-larvae (PL), and social displacement have resulted in negative environmental and social impacts. As a consequence, a number of industry, academic and environmental groups have moved quickly to develop identifiable sets of Better Management Practices (BMPs) aimed at reducing any potentially negative environmental and social impacts of this activity.

It is not the intent of this study to enter into the debate of whether, if, how, where, or when negative impacts may have occurred from shrimp farming. The intent of this study was to conduct an economic evaluation of sets of BMPs that have been developed for shrimp farming and to identify what economic impacts might result from their adoption.

Better Management Practices are generally viewed as a more sensible alternative to the development of regulations since the enforcement and monitoring of strict guidelines may prove to be unfeasible in many shrimp-growing regions (Boyd and Haws 1999). The flexible nature of BMPs may represent a more rapid and efficient approach to reduce or prevent potentially negative impacts on the environment. General codes of conduct and practice have been formulated by the Global Aquaculture Alliance (GAA), a shrimp industry group, and the Food and Agriculture Organization of the United Nations (FAO) (Boyd 1999; FAO 1997). Two nongovernmental environmental organizations, the Industrial Shrimp Action Network and the Environmental Defense Fund, have also developed their own codes of generic BMPs.

Shrimp aquaculture can take many forms. Moreover, potential implications for the environment also are heavily dependent on local conditions. For these reasons, there is a current trend to develop voluntary codes of practice or sets of BMPs for specific countries or growing areas. For example, the Association of Southeast Asian Nations (1997) prepared a summary manual of good shrimp farm management practices while Donovan (1997) and Dixon (1997) formulated specific codes of practice for the shrimp farming industries of Australia and Belize, respectively.

A recent project from the University of Rhode Island (URI, USA) has resulted in the identification and discussion of Good Management Practices (GMPs) for the shrimp culture industry in Latin America, with a special focus on Honduras (Boyd et al. 2001). The URI report presents specific management recommendations that can reduce potentially negative environmental impacts and/or improve production efficiency of shrimp farming. While farmers have begun to realize the importance of implementing BMPs (or GMPs) on the daily operation of their farms, little research has been conducted to analyze the economic implications of these practices. A clear evaluation and presentation of the economic gains associated with BMPs may increase their rate of adoption.

The objective of the present analysis is to develop estimates of the economic implications associated with a selected group of those BMPs that are most likely to improve the quality and/or reduce the volume of effluents of shrimp farms in Honduras and Nicaragua. This analysis was based on a mathematical programming model developed by Valderrama (2000) for the economic optimization of shrimp culture in Honduras. The conceptual framework of this model is expanded in this analysis to allow for the incorporation of an environmental component and the development of appropriate technical coefficients for each of the selected BMPs. Results of this analysis will provide a measure of the economic incentives or trade-offs between environmental and economic gains associated with various BMPs.

The first part of this report will present a non-technical exposition of the Valderrama (2000) economic optimization model. This overview will provide the general reader with a clear understanding of the structure and working mechanics of the model as well as its inherent flexibility to analyze various aspects of shrimp farming. Following this, an explanation of the environmental component of the model, which was developed based on partial nutrient budgets specifically formulated for shrimp farming in Honduras, will be provided. Subsequently, the environmental and economic implications of five BMPs (reduction of water exchange rates, reduction of production levels, feed trays, settling basins, and recirculation through a mangrove biofilter) for Honduran shrimp farms of three sizes will be examined. Finally, a related analysis will be conducted to evaluate the effects of the same group of BMPs on the profitability of artisanal shrimp farms in Honduras and small cooperatives in Nicaragua.

The Mathematical Model

The objective of the mathematical model was to formulate profit-maximizing annual plans of activities for each of three farm-size scenarios: small (73 ha), medium (293 ha), and large (966 ha) farms. These plans of activities would contain specific instructions to the farm manager regarding stocking and harvesting dates, stocking densities, water exchange strategies, and rotation of ponds within the farm. These are very important production decisions continuously facing farm managers, and they determine to a large extent the financial success of an operation. To formulate the profit-maximizing plans of activities, an economic optimization technique called Linear Programming (LP) was used in combination with production information provided by three cooperating shrimp farms in Honduras. This information consisted of an aggregated three-year (1997-1999) dataset of pond production records, with each record corresponding to a complete pond growout cycle. Production records provided specific information on pond size, shrimp species, origin of postlarvae (PL), stocking and harvesting dates, stocking density, survival rate, average growth rate, and feed conversion ratio (FCR) as reported by the participating farms. The primary species in the records was *Litopenaeus vannamei* and the majority of the post-larvae stocked was hatchery-reared.

Given this context, the objective of the LP model was to maximize annual net income realized by a shrimp farm operation. To achieve this, control variables needed to be identified and optimized. Control variables are all those aspects of production that the farmer can manipulate to increase the profitability of the operation. In this case, identified variables were stocking densities, stocking and harvesting dates, and water exchange rates. What Linear Programming specifically does is to provide the user with special mathematical procedures to process all relevant production information in order to estimate the optimal levels of the control variables. In other words, LP can be used to determine which specific combination of stocking densities, stocking and harvesting dates, and water exchange rates will lead to maximization of net farm income in Honduran shrimp farms.

The evolution of the shrimp farming industry in Honduras underscores the relevance of current research on economic optimization of farm practices. Along with most shrimp-growing regions in the Western Hemisphere, the industry has been strongly affected by the introduction of shrimp viral diseases. Two major viral epizootics, Taura Syndrome Virus (TSV) and White Spot Syndrome Virus (WSSV), have provoked a chronic reduction in survival rates of approximately 30% on Honduran shrimp farms. The first TSV outbreak was reported in 1994 (Hasson et al. 1997) while WSSV apparently was introduced in 1999 (Jory and Clifford 1999). Historic survival rates (before 1994) ranged from 60 to 80%; however, they have ranged from 30 to 50% (rainy season) and from 15 to 30% (dry season) during the post-Taura years (Boyd et al. 2001). The successive onset of viral diseases, coupled with the catastrophic effects of Hurricane Mitch in October 1998, have led farmers to reconsider pond management strategies and to seek greater economic efficiency through optimization of farm practices and greater awareness of costs (Boyd et al.

2001). Many farm managers state that they are now attempting to maximize farm profit rather than pond yield, which represents a major paradigm shift for the industry. However, there still exists some degree of confusion as to how this could be achieved, as evidenced by a recent survey of farm management practices (Boyd et al. 2001). For example, there is no general agreement as to which population density in ponds would lead to profit maximization, or the optimal duration of growout cycles. All these factors provided a rationale for the development of the economic optimization model.

Basically, what the model does is to compare the relative profitability of production cycles initiated in every month of the year. Besides evaluating seasonal variations, the model also takes a look at the relative profitability of different stocking densities, cycle lengths, and water exchange rates within a given stocking month. Three stocking densities (low, intermediate, and high) and three cycle lengths (short, intermediate, and long) were considered in each month, and specific options varied with the climatic seasons. Table 1 shows the complete range of options during the dry and rainy seasons. Higher stocking densities and longer grow-out cycles were selected for the rainy season because higher pond yields can be obtained as compared to the dry-season cycles. Teichert-Coddington et al. (1994) demonstrated that the seasonal variations in Honduran shrimp production were primarily due to changes in average water temperature. Growth rates during the rainy season are typically higher because of higher water temperatures.

Table 1. Selection of stocking densities and lengths of grow-out cycles used in the definition of monthly production activities for the economic optimization of shrimp farming in Honduras.

	Stocking density (PL/m^2)	**Length of growout cycle (weeks)**
Dry season (October-March)	5, 12, 20	11, 15, 19
Rainy season (April-September)	5, 15, 25	13, 17, 21

In addition to the stocking density and cycle length options, two water-exchange regimes were considered. The first corresponded roughly to exchange rates historically used in Honduras (daily exchange of 10% of pond volume, beginning in week 4) while a regimen of lower exchange rates (5% daily) was proposed as an alternative. Results of recent research (Green et al. 1999) indicate that traditional water exchange rates used in Honduras can be drastically reduced without affecting pond yield and mean size at harvest. Indeed, these findings have motivated many farmers to reduce exchange rates, with many of them operating already at the 5% level. The inclusion of the two exchange rates in the model allowed an economic comparison between the traditional and current water exchange strategies being used in Honduras.

All possible combinations of stocking densities, duration of grow-out cycles, and water exchange regimens resulted in a total of 18 different production activities per month (216 per annum) taken into consideration by the model. Estimates of net returns/ha were calculated for each production activity within each farm size scenario to account for certain economic effects associated with the size of the operations. Namely, it has been found that larger farms in Honduras pay a lower price for feed, which greatly enhances their potential for profit (Valderrama 2000). Other differences among farm scenarios have been summarized in Table 2. Table 3 presents estimates of net returns/ha calculated for nine production activities initiated in October (dry season), April and July (rainy season) for a medium farm (293 ha). The most important variable costs (seed, feed, fuel, and post-harvest and marketing costs) were accounted for in the estimation of net returns/ha. As commented earlier, profitability is much reduced by operating in the dry season as compared to the rainy season. It should also be noted that high stocking densities do not necessarily lead to greater profits; for instance, stocking at intermediate densities in April yields higher returns that stocking at high densities in July (Table 3).

Table 2. Distinctive characteristics of farm-size scenarios defined in the economic optimization model for shrimp farming in Honduras.

	Farm-size scenario		
	Small farms	**Medium farms**	**Large farms**
Pond area (ha)	73	293	966
Unit price of feed (US$/metric ton)	595	468	331
Limitations in the monthly supply of post-larvae (PL)	≤ 5 million	None	None
Fixed costs (US$/ha)	1,545	1,342	1,160

Through Linear Programming, all available information was processed and the optimal combination of production activities (Annual schedule of operations) was identified for each farm-size scenario. It should be noted that the solutions provided by the model are shaped by the type of assumptions and constraints that are built into it. However, the model structure is rather flexible, allowing the user to easily introduce modifications to the original set of assumptions to analyze the effects of these changes in model output. The present study takes advantage of this flexibility to analyze the economic and environmental implications of five BMPs. To this end, an environmental component was created whereby specific environmental impacts (In the form of effluent discharges) were defined for each production activity in the model. Because the BMPs considered in this study are aimed at reducing nutrient discharges from shrimp farms, Linear Programming represents an excellent tool to analyze the effects of BMPs on the composition of optimal schedules of operations in order to meet some pre-established water quality criteria.

Table 3. Estimated 2001 costs and returns (US Dollars) above selected variable costs for nine production activities specified in the medium shrimp farm scenario (293 ha) of the economic optimization model for shrimp farming in Honduras.

Weeks	Survival rate (%)	Tail yield (kg/ha)	Count size (no./lb)	Price (US$/kg)	Gross receipts (US$/ha)	Seed cost [a] (US$/ha)	Feed cost [b] (US$/ha)	Fuel cost [c] (US$/ha)	Post-harvest and marketing costs [d] (US$/ha)	Net returns (US$/ha)
Production cycles of varying lengths stocked in October (dry season) at 5 PL/m^2. High water exchange rates.										
11	16	48	71-90	8.93	426	250	55	79	92	-49
15	16	56	61-70	9.15	510	250	85	118	108	-51
19	16	59	61-70	8.56	503	250	117	157	113	-136
Production cycles of varying lengths stocked in April (rainy season) at 15 PL/m^2. Low water exchange rates.										
13	46	531	51-60	7.61	4,045	750	395	49	1,026	1,824
17	46	604	51-60	7.61	4,594	750	591	69	1,166	2,018
21	46	633	41-50	8.60	5,442	750	793	89	1,222	2,589
Production cycles of varying lengths stocked in July (rainy season) at 25 PL/m^2. High water exchange rates.										
13	40	523	71-90	6.58	3,439	1,250	434	98	1,009	647
17	40	551	71-90	6.58	3,623	1,250	599	138	1,063	573
21	40	551	71-90	6.00	3,303	1,250	767	177	1,063	46

[a] It is assumed that ponds are 100% stocked with hatchery-raised PL, at a cost of US $5/1,000.

[b] Feed unit cost = US $468/metric ton.

[c] Fuel cost = (L of water/ha) * (% water exchange) * (1/capacity of pump in Lpm) * (no. of days) * (1/60 min) * (14.4 L diesel/h) * (US$0.52/L of diesel).

[d] Includes ice, hauling, processing, and sea freight costs, as well as broker and export fees.

Results of the LP Model under a Regime of High Water Exchange Rates

A first model simulation was run to identify baseline annual net returns and profit-maximizing management strategies under traditional industry conditions, i.e., using high water exchange rates (10% daily). Net returns above the most important variable costs (seed, feed, fuel, post-harvest handling, and marketing costs) were US$3,870; US$5,378 and US$5,985 for the small, medium, and large farms, respectively (Table 4).

For the medium and large farm scenarios, the profit-maximizing combination of production activities consisted of three clearly defined seasonal production blocks, corresponding to the dry season, a transition period, and the rainy season (The dry season lasts from October through March while the rainy season lasts from April to September). In the rainy season, the model recommended long production cycles (21 weeks) stocked in June at intermediate densities (15 PL/m^2). Intermediate densities were selected because yields are higher than those achieved at lower densities and growth rates are not impacted by overcrowding effects, as observed at higher stocking rates (25 PL/m^2). Approximately 30% of the farm area (93 and 266 ha for the medium and large farms, respectively) was harvested in week 17. The remaining production area was scheduled for harvest 4 weeks later, in week 21. This particular harvesting arrangement conforms to a pre-determined model constraint whereby no more than 70% of total farm area can be harvested in any given 2-week period so as not to exceed the labor and machinery capabilities of the farms. During the dry season, production was focused on the November cycles, with 30% of the pond area being harvested at the end of week 11 to free up resources for harvesting four weeks later (week 15). Unlike the rainy season cycles, high stocking densities (20 PL/m^2) were selected in November because the production records indicated no significant density-dependent growth effects in this particular stocking month. The reasons why this occurs are not easy to identify, but it may be related to a particular combination of environmental factors (favorable salinity levels a few weeks into the dry season).

The selected February and March cycles fall in a transition period between the two climatic seasons. The March cycle is terminated in week 11 to allow re-stocking of the same production area in June. High stocking densities (20 PL/m^2) were again selected in February because density-related effects on growth rates were negligible.

The optimal solution identified for the small-farm scenario involved a more varied mix of production activities, with no clearly defined seasonal production blocks. This occurred because small farms are constrained by the number of PLs that they can acquire at one time, resulting in a limitation of the total number of hectares that can be stocked within a given month. Valderrama (2000) explained that small farms in Honduras frequently lack the infrastructure to handle more than 5 million PL per month (Table 2). As a result, total pond area available for stocking in November, March, and June was limited to 25, 42, and 33 ha, respectively. This called for additional production cycles being initiated in October, January, April, July, and August. The combination of higher feed prices and limitations in the supply of PL led to a substantial decline in net returns/ha for the small farms as compared to the other farm-size scenarios.

It should be noted that these model results differ slightly from those of Valderrama (2000). The difference arose from the updated 2001 prices used in the new simulation. Shrimp prices in 2001 were in general much lower than the 1998 prices used in the original model.

Table 4. Summary of production activities selected in the resolution of the high water exchange rates (10%) scenario in the economic optimization model for shrimp farming in Honduras.

Production activities				Number of allocated ha			Expected tail count (no./lb)
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	High rate	23			71-90
October	12	15	High rate	18			61-70
November	20	11	High rate		93	266	71-90
November	20	15	High rate	25	200	700	61-70
January	12	11	High rate	30			71-90
February	20	11	High rate		93	266	71-90
February	20	15	High rate	2			61-70
March	12	11	High rate	42	200	700	61-70
April	15	13	High rate	30			51-60
June	15	17	High rate		93	266	41-50
June	15	21	High rate	33	200	700	41-50
July	5	21	High rate	10			31-35
August	5	21	High rate	30			41-50
Net income/ha over selected variable costs (US$)				3,870	5,378	5,985	

Estimating Net Returns Above Total Costs of Production

The original Valderrama (2000) mathematical model estimated potential net returns above the most important variable costs for Honduran shrimp farms to examine alternative management strategies. Many proposed BMPs, however, involve a significant amount of investment in farm infrastructure. Therefore, the model was further refined to include fixed costs and additional variable costs associated with equipment, levees, and other capital items (Table 5). Discounting these costs from the estimated net returns above the most important variable costs yields US$ 1,192; US$ 3,355 and US$ 4,237/ha in total net returns above all costs of production for the small, medium, and large farms, respectively.

Incorporating Environmental Constraints

The economic evaluation of BMPs required the development of a set of constraints in addition to the technical, production-related restrictions originally defined in the model. The BMPs considered in this part of the analysis were: 1) Reduced water exchange rates. 2) Reduced production levels. 3) Improved feed management through the use of feed trays. These BMPs all focus on reducing either the volume of water discharged (source reduction) or the concentration of nutrients in the water discharged.

Table 5. Annual estimates of labor, gas, chemicals, repairs, and fixed costs (US Dollars) for Honduran shrimp farms of three different sizes.

Item	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)
Variable Costs			
Labor	40,784	94,118	219,608
Gas	3,185	6,297	42,513
Chemicals	2,615	5,745	11,427
Equipment and pond repairs	36,078	93,508	294,385
Subtotal	82,663	199,667	567,933
Fixed Costs			
Interest on investment	44,771	166,188	325,290
Overhead expenses	19,609	76,870	241,671
Security	9,694	26,245	183,535
Depreciation	38,599	123,312	368,764
Concession	131	458	1,569
Subtotal	112,805	393,073	1,120,827
Total cost	195,468	592,740	1,688,760
Total cost/ha	2,678	2,023	1,748

The first step in developing environmental constraints was to measure the net amount of nutrient discharge to be generated by each production activity specified in the model. These amounts were derived using partial nutrient budgets developed by Teichert-Coddington et al. (2000), the only known chemical budgets for semi-intensively managed commercial shrimp ponds in Latin America. In this study, mass nutrient exchange (the difference between nutrient gain and nutrient loss) due to water exchange in a 100-day production cycle was calculated for total alkalinity, total nitrogen (TN), total ammonia nitrogen (TAN), nitrate + nitrite nitrogen (TAN and nitrate-nitrite nitrogen are known collectively as dissolved inorganic nitrogen, or DIN), total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll a, chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5). These estimates were based on data from 14 different ponds sampled from different farms during both climatic seasons. In addition, partial TN and TP budgets were developed for each sampled pond itemizing the different sources (gain) and fate (loss) of each nutrient throughout the production cycle.

Teichert-Coddington et al. (2000) reported that there is a mean net discharge (The concentration of the nutrient is higher in the effluent than in the source water) of TN, TP, SRP, chlorophyll a, COD and BOD_5 by water exchange. In contrast, there is a mean net intake (effluent concentration is lower than source water concentration) of total alkalinity and DIN. Given that it is the preferred source of nitrogen for phytoplankton, DIN appears to be removed from the pond water by phytoplankton, while most of the exported TN comes in the form of particulate matter. Although there is a net discharge of SRP in the effluent, there also appears to be a balance between the supply water and the pond effluent, which can be attributed to phytoplankton activity.

Table 6 presents a representative partial nitrogen and phosphorus budget based on data from the 14 ponds sampled in the Teichert-Coddington et al. (2000) study. Gains of nitrogen and phosphorus occurred from water exchange, stocking shrimp PL, and the addition of feed and fertilizer (Reportedly, only five of the 14 ponds were fertilized). Nutrients were lost through water exchange, shrimp harvest, and during pond drainage. The indicated pond drainage loss refers to the net nutrient discharge after accounting for the initial nutrient input from pond filling. Mean net discharge of TN and TP by water exchange was –10.7 kg/ha-100 days (This is the difference between the columns N gain and N loss-water) and –1.3 kg/ha-100 days, respectively. Unaccounted for fractions of TN and TP (either retained in the pond bottom or lost to the atmosphere) amounted to 7.96 and 6.7 kg/ha-100 days, representing about 6.5% and 30.8% of the initial inputs of nitrogen and phosphorus, respectively. Finally, the budgets indicated that each kilogram of feed nitrogen and phosphorus applied to ponds resulted in 0.21 kg of net nitrogen discharge and 0.16 kg of net phosphorus discharge by water exchange.

The nutrient discharge-feed nutrient content ratios give an important indication of the impact of feeding rates on the net nutrient load exported to the estuaries via water exchange. To further explore this relationship, regression analyses were conducted to describe variations in nitrogen and phosphorus loss rates by water exchange in terms of the inputs from water exchange (columns N and P gain-water in Table 6), fertilizer and feed additions, and water exchange rates. Analyses were also run to establish the same relationship between net nutrient loss by pond drainage and the addition of feed and fertilizers.

The analysis for nitrogen indicated a significant effect of the initial load of N in the source water, amount of water exchanged, and N input in feed on the rate of nitrogen loss by water exchange. No significant effect of N input in fertilizer was found. The estimated regression equation was

$$(1)\ N_{loss-water} = 0.531 N_{gain-water} + 0.602\,Water + 0.507 N_{feed} \quad \mathrm{F} = 16.42\ (\mathrm{P} << 0.05)$$

where $N_{loss-water}$ and $N_{gain-water}$ are the quantities of TN leaving and entering the pond by water exchange, respectively, in kg/ha-100 days; *Water* is the total volume of water exchanged in a 100-day growout cycle (Thousand m^3) and N_{feed} is the total input of feed N (kg/ha-100 days). All coefficients were significant at the 0.05 α level.

The regression analysis for phosphorus revealed a significant effect of phosphorus gain during water exchange and both feed and fertilizer applications on the rate of phosphorus loss by water exchange. However, water exchange rate did not appear to affect the loss rate, which is contrary to the expectation that greater phosphorus quantities should be exported from ponds with higher water exchange rates. This lack of correlation may be due to the significantly greater effect of pond fertilization and the initial concentration of phosphorus in the water supply, the combination of which may have masked any potential effect of higher water exchange rates.

Unlike water exchange, the analysis with the pond drainage data did not reveal any significant effect of feed or fertilizer addition on net nitrogen or phosphorus discharges during pond drainage. This may be due to the re-suspension of organic matter attached to bottom soil particles that occurs during the last stages of pond draining. Teichert-Coddington et al. (2000) reported a marked increase in TN and TP water concentrations in the last 10% of pond volume during pond draining in Honduran shrimp farms. This spike in concentrations induced by pond sediment stirring by shrimp and the seining crew may be masking any interaction between feed and fertilizer applications and net nutrient discharge.

Table 6a. Partial nitrogen budget and nitrogen discharge by water exchange per unit of nitrogen input in feed. Entries were calculated as the average of 14 ponds. Taken from Teichert-Coddington et al. (2000).

Nitrogen gain (kg/ha – 100 days)					Nitrogen loss (kg/ha – 100 days)				Balance (gain-loss)	N discharge/ feed N[e]
Water[a]	Fertilizer	Feed[b]	Shrimp	Total	Water	Shrimp[c]	Pond drainage[d]	Total		
77.0	1.3	43.8	0.45	122.5	87.7	17.1	9.7	114.6	7.96	-0.21

[a] Average water exchange rate = 5.0%.
[b] Feed dry matter = 92%. Mean nitrogen content in feed dry matter = 3.7%.
[c] Mean percentage of nitrogen in *Litopenaeus vannamei* dry matter: 11.2%.
[d] Pond drainage = total nutrient discharge during drainage less nutrient input from initial pond filling.
[e] Nitrogen discharge by water exchange is computed as the difference between the columns N gain-water and N loss-water.

Table 6b. Partial phosphorus budget and phosphorus discharge by water exchange per unit of phosphorus input in feed. Entries were calculated as the average of 14 ponds. Taken from Teichert-Coddington et al. (2000).

Phosphorus gain (kg/ha – 100 days)					Phosphorus loss (kg/ha – 100 days)				Balance (gain-loss)	P discharge/ feed P[e]
Water[a]	Fertilizer	Feed[b]	Shrimp	Total	Water	Shrimp[c]	Pond drainage[d]	Total		
10.8	0.5	10.0	0.0	21.3	12.1	1.9	1.0	14.6	6.7	-0.16

[a] Average water exchange rate = 5.0%.
[b] Feed dry matter = 92%. Mean phosphorus content in feed dry matter = 0.84%.
[c] Mean percentage of phosphorus in *Litopenaeus vannamei* dry matter: 1.25%.
[d] Pond drainage = total nutrient discharge during drainage less nutrient input from initial pond filling.
[e] Phosphorus discharge by water exchange is computed as the difference between the columns P gain-water and P loss-water.

Because of the significant interactions between feed and water exchange rates and TN loss by water exchange, equation (1) was used to predict the exported amounts of TN via water exchange associated with each production activity in the mathematical model. The assumed concentration of TN in the intake water was 0.87 mg/l, according to inlet water quality reports for one of the participating shrimp farms (Green et al. 1998). Applied amounts of feed and water exchange rates are defined implicitly within each production activity. The phosphorus regression equation was disregarded because of its failure to document the effect of water exchange on the levels of phosphorus discharge. Fertilization appeared to be the most important factor influencing phosphorus losses by water exchange; however, the farms that provided information for the model practiced little or no fertilization at all because they are located on riverine sites with high natural concentrations of TP. Teichert-Coddington et al. (2000) reported estuarine concentrations of TP of 0.25 mg/l in both dry and rainy seasons, while reports by Green et al. (1998) ranged from 0.14 to 0.19 mg/l.

To obtain an approximate estimate of the net release of TP by water exchange in unfertilized ponds, a factor was obtained using data from unfertilized ponds reported by Teichert-Coddington et al. (2000) which calculates the net amount of P discharge per unit of phosphorus input in feed per unit volume of water. This factor was found to be 4.10 kg of net phosphorus discharge per kg of phosphorus feed per one million cubic meters of water exchanged. This number was then used to calculate net phosphorus discharges by water exchange for each production activity in the model.

In addition to water exchange, net discharge of nutrients also occurs during pond drainage. Given the lack of correlation between net discharge at drainage and feed, fertilization, and water exchange rates, the average net discharges of TN and TP reported by Teichert-Coddington et al. (2000) (9.7 and 1.0 kg/ha, respectively) were assumed for all production activities.

In addition to TN and TP, attempts were made to estimate net discharges of SRP and BOD_5 by water exchange and pond drainage. Although Teichert-Coddington et al. (2000) report an average mean net discharge of SRP by water exchange (-0.171 kg/ha-100 days), they also recorded a mean net loss of 2.0 kg/ha-100 days in fertilized ponds, whereas a mean net gain of 1.84 kg/ha-100 days was recorded in unfertilized ponds. As such, no net discharge of SRP was assumed in this model. As for BOD_5, an estimated net loss by water exchange of 2.22 kg of BOD_5 per kg of feed per one million cubic meters of water exchanged was obtained from the Teichert-Coddington et al. (2000) data, as well as a net discharge by pond drainage of 24 kg/ha (Assuming an intake BOD_5 concentration of 6.6 mg/l and an average concentration during draining of 9.0 mg/l).

Table 7 presents estimates of net discharges of TN, TP, and BOD_5 by water exchange and pond drainage for nine production activities based on expected pond yields and FCRs. These estimates were used in the definition of environmental constraints for the model.

Effluent Standards for Shrimp Aquaculture

Boyd and Gautier (2000) prepared a list of initial and target standards for shrimp farm effluents based on permits already developed for effluents of other activities. The GAA promotes voluntary compliance of these standards by shrimp farmers worldwide. However, the ability to comply with suggested standards is contingent upon a variety of factors such as level of production, farm size and local environmental conditions.

Table 7. Estimated net discharges (kg/ha) of TN, TP, and BOD_5 by water exchange and pond drainage for nine production activities defined in the economic optimization model for shrimp farming in Honduras.

Length of growout cycle (weeks)	Survival rate (%)	FCR	Tail yield (kg/ha)	TN (kg/ha)			TP (kg/ha)			BOD_5 (kg/ha)		
				Net loss by water exchange	Net loss by pond drainage	Total net loss	Net loss by water exchange	Net loss by pond drainage	Total net loss	Net loss by water exchange	Net loss by pond drainage	Total net loss
Production cycles of varying lengths stocked in October at 5 PL/m^2. High water exchange rates (10%).												
11	18	2.09	48	11.2	9.7	20.9	0.17	1.0	1.17	11.6	24.0	35.6
15	18	2.79	54	16.9	9.7	26.6	0.39	1.0	1.39	27.1	24.0	51.1
19	18	3.64	56	22.7	9.7	32.4	0.71	1.0	1.71	49.8	24.0	73.8
Production cycles of varying lengths stocked in April at 15 PL/m^2. Low water exchange rates (5%).												
13	46	1.08	513	19.8	9.7	29.5	0.77	1.0	1.77	53.8	24.0	77.8
17	46	1.42	579	28.9	9.7	38.6	1.60	1.0	2.60	112.3	24.0	136.3
21	46	1.82	603	38.3	9.7	48.0	2.76	1.0	3.76	193.5	24.0	217.5
Production cycles of varying lengths stocked in July at 25 PL/m^2. High water exchange rates (10%).												
13	41	1.36	568	31.5	9.7	41.2	2.19	1.0	3.19	153.6	24.0	177.6
17	41	1.79	611	45.0	9.7	54.7	4.44	1.0	5.44	310.5	24.0	334.5
21	41	2.29	627	59.4	9.7	69.1	7.63	1.0	8.63	534.1	24.0	558.1

Therefore, Boyd and Gautier (2000) recommended first to comply with the proposed initial standards and then, as more information becomes available, additional efforts could be made to meet the more restrictive target standards.

The proposed standards include six water-quality parameters (Table 8). Teichert-Coddington et al. (2000) characterized mass nutrient exchanges for three of them (TP, TAN, and BOD_5). As discussed before, TAN appears to be removed from pond water by phytoplankton activity on Honduran shrimp farms. Therefore, environmental constraints in this analysis were defined with respect to TP and BOD_5. It is hypothesized that improvements in the concentrations of other water quality parameters will be concomitant with reductions in TP and BOD_5 net discharges.

The suggested standards are useful in that they impose concentration limits for the parameters of concern. However, they do not measure the impact of continued discharge on the receiving waters. To address this issue, the environmental constraints were defined in terms of both the concentration of nutrients and total volume of water exchanged as a result of farm operation. In simple terms, the environmental constraints work by estimating the average daily net discharge (kg/farm/day) of nutrients in the farm and comparing it to a discharge limit based on suggested standard concentrations and a pre-determined effluent volume. Average daily amounts of net discharge were derived from the estimates of net nutrient discharges associated with each production activity (Table 7). On the other hand, discharge limits were computed based on the initial standards for TP and BOD_5 (0.5 and 50 mg/l), a water exchange rate of 5%, and an initial concentration of 1.9 mg/l for TP and 6.6 mg/l for BOD_5 in the source water. In other words, allowed net discharge quantities are those that are not going to increase TP and BOD_5 concentration above the standard levels in a volume of water equal to 5% of farm pond volume. As the model includes activities with exchange rates of 5 and 10%, the resulting effect is that the 10%-exchange activities are twice as likely to raise pond effluent concentrations above standard levels than the 5% activities, giving the model an incentive to select low water exchange activities on the premises of reduced nutrient discharge.

Limit discharges were also computed based on the TP and BOD_5 target standards (0.3 and 30 mg/l, respectively) and a water exchange level of 5%. Running model simulations under both discharge limits would provide an indication of the effects on net farm income and optimal management strategies associated with each standard level. Discharge limits were also calculated assuming a water exchange level of 2%. This would reflect a scenario in which farmers would be allowed to operate using 5 and 10% exchange rates but would be forced to meet stricter discharge standards.

It must be noted that environmental constraints were defined with respect to water exchange and not pond drainage. The reason for this is that net discharge of nutrients by water exchange appears to be influenced by pond management decisions such as levels of feeding and water exchange while net discharge by pond drainage is more related to the degree of disturbance of the pond bottom by seining and raking. Discharge of solids at harvest can be reduced by good pond construction practices such as well sloped and graded bottoms to promote good drainage, and catch basins to help concentrate shrimp before removal (Teichert-Coddington et al. 1999). Any other technique that effectively slows down discharge velocity of pond effluent during the last phase of draining may prove to be useful in reducing discharge amounts (Boyd et al. 2001).

Table 8. Suggested initial and target water quality standards for shrimp farm effluents. Taken from Boyd and Gautier (2000).

Variable (Units)	Initial Standard	Target Standard
pH (standard units)	6.0-9.5	6.0-9.0
Total suspended solids (mg/l)	100 or less	50 or less
Total phosphorus (mg/l)	0.5 or less	0.3 or less
Total ammonia nitrogen (mg/l)	5 or less	3 or less
5-d biochemical oxygen demand (mg/l)	50 or less	30 or less
Dissolved oxygen (mg/l)	4 or more	5 or more

Estimating Average Total and Net Nutrient Discharge under the Base Scenario of High Water Exchange Rates (10%)

The estimates of TN, TP, and BOD_5 net discharges (Table 7) can be used to compute overall nutrient loads associated with the plans of production outlined by the LP model (Table 4). Table 9 presents daily average total and net discharge quantities for each farm-size scenario assuming a water exchange rate of 10% per day. Pond drainage discharges are also included in these estimates. The total nutrient discharge is the quantity of nutrients being released from the ponds, while the net discharge is the actual contribution of in-pond processes. Overall, at a 10% water exchange rate, 38, 21 and 31% of the total discharge of TN, TP and BOD_5 can be attributed to shrimp pond management.

The Effect of Reduced Water Exchange Rates

The first BMP considered in this analysis was the reduction of daily water exchange rates from 10% to 5%. Water exchange has been typically used in Central America in the belief that it improves water quality by removing wastes, increasing dissolved oxygen (DO) concentrations, and maintaining desired salinity ranges (Boyd et al. 2001). Honduran farmers rely on water exchange because mechanical aeration is rarely used (Teichert-Coddington et al. 1996). Recent research has indicated that historic water exchange rates (10-15%) are ineffective at improving water quality or pond yields (Green et al. 1999). Moreover, most farmers now view high water exchange rates as a risky practice because it increases the chances of introducing disease vectors and contaminants into ponds. As a result, many farmers have reduced water exchange rates to an average of 5%.

Table 10 summarizes the results of the linear programming models including both high and low-exchange production activities. The model selected only activities with low exchange rates because fuel costs were lower and pond yields were unaffected by the lower rates of exchange. Net returns/ha above the most important variable costs were US$ 4,191; US$ 5,565 and US$ 6,173 for the small, medium and large farms, respectively, an increase of 8, 3 and 3% with respect to the baseline scenario of high water exchange rates (Table 4). Net returns/ha above all costs of production were estimated at US$ 1,513; US$ 3,542 and US$ 4,425, respectively. The difference in net returns between the two scenarios corresponds to additional income that is already being realized on those farms that practice water exchange rates of 5%.

Table 9. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 10%. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD$_5$**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	73.18	25.71	12.59	2.22	485.21	125.13	54,559
Medium farms (293 ha)	278.76	109.22	47.85	10.82	1,932.71	646.52	194,877
Large farms (966 ha)	926.43	362.81	159.29	36.20	6,445.07	2,169.35	647,836

Other than the reduction in water exchange rates, no other changes in the optimal mixes of activities were observed for the medium and large farms. Production cycles should be initiated in November (dry season), February-March (transition period), and June (rainy season). In contrast, some changes occurred in the small farm scenario relative to the baseline results (Table 4). Of the 42 ha allocated to the 11-week March cycle, 23 ha are now harvested 4 weeks later (The cycle is extended to 15 weeks). In addition, 13 ha are transferred from the 13-week April activity to the 21-week July cycle. The number of hectares stocked in April dropped from 30 (Table 4) to 17, while this number increased in July from 10 to 23. Similarly, a total of 13 ha were transferred from the 11-week January cycle to the 15-week February cycle, and also from the 11-week to the 15-week cycle in October. The rationale for these changes is that the relative profitability of long production cycles increases when water exchange rates are reduced, as compared to shorter cycles. For example, as exchange starts in week 4 of each cycle, reducing exchange rates results in pumping cost savings during 8 of the 11 weeks of a short cycle (73% of the cycle), whereas savings are realized during 12 of the 15 weeks of an intermediate cycle (80%). Thus, given the varied mix of activities in the small farm scenario, reducing water exchange rates brings about an increase in the duration of growout cycles.

Besides lowering costs of operation, reduced water exchange rates have the additional benefit of reducing net nutrient discharges from the pond system. Table 11 presents the total and net nutrient load for each farm-size scenario assuming a 5% water exchange rate. Relative to the previous scenario of high water exchange rates (Table 9), net discharge (The portion of total discharge attributable to pond operation) of TN, TP, and BOD$_5$ decreased by 16, 37, and 44%, respectively. Thus, nutrient loads to receiving estuaries can be significantly reduced by just reducing traditional exchange rates to a 5% level.

Table 10. Summary of production activities selected in the resolution of the economic optimization model for shrimp farming in Honduras. In this particular simulation, the model was given the option of selecting between high and low water exchange rates.

Production activities				**Number of allocated ha**			**Expected tail count (no./lb)**
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	Low rate	10			71-90
October	12	15	Low rate	31			61-70
November	20	11	Low rate		93	266	71-90
November	20	15	Low rate	25	200	700	61-70
January	12	11	Low rate	17			71-90
February	20	11	Low rate		93	266	71-90
February	20	15	Low rate	15			61-70
March	12	11	Low rate	19	200	700	61-70
March	12	15	Low rate	23			51-60
April	15	13	Low rate	17			51-60
June	15	17	Low rate		93	266	41-50
June	15	21	Low rate	33	200	700	41-50
July	5	21	Low rate	23			31-35
August	5	21	Low rate	17			41-50
Net income/ha over selected variable costs (US$)				4,191	5,565	6,173	
Net income/ha above total costs (US$)				1,513	3,542	4,425	

Table 11. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 5%. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD_5**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	48.08	21.29	7.32	1.47	277.42	74.18	30,795
Medium farms (293 ha)	187.85	92.61	27.41	6.61	1,074.72	352.16	109,479
Large farms (966 ha)	623.88	307.54	91.16	22.07	3,579.82	1,179.95	363,616

It should be noted that, while clear economic and environmental gains result from reducing daily exchange rates, Green et al. (1999) indicated that routine water exchange may not be necessary to maintain water quality and sustain pond yields on Honduran farms. At a minimum, daily exchange can be delayed until week 10 of the production cycle. They also suggested that monitoring of DO concentrations should be used as a management criterion to trigger water exchange, i.e., water should be exchanged only in response to projected low DO episodes. In spite of these recommendations, many Honduran farms still exchange water on a daily basis (Boyd et al. 2001). Many farm managers view the use of water exchange to combat low DO episodes as too risky. Routine water exchange may be needed to keep salinity within desired levels during the dry season, depending on the location of the farm.

Performing water exchange following a pre-determined management criterion would bring about significant gains for shrimp farms in terms of reduced production costs and nutrient loadings to estuaries, provided that pond yields can be sustained. The analysis of additional BMPs in this study, however, will be based on the assumption of 5% daily water exchange so as to accurately reflect the impact of BMPs given the current characteristics of the Honduran shrimp industry.

Effects of Introducing Net Discharge Limits on Farm Production Levels

Table 12 presents the various TP and BOD_5 net discharge limits (kg/day/farm) calculated for each farm-size scenario based on the initial and target GAA standards for each of two effluent volumes (5 and 2% pond volume). The model allowed the farm manager to select a water exchange rate of either 5 or 10%, but discharge limits were based on a quantity of effluent equivalent to water exchange rates of 5 and 2%. The initial standard concentrations were 0.5 mg/l for TP and 50 mg/l for BOD_5, while target standards were 0.3 mg/l for TP and 30 mg/l for BOD_5.

Model simulations were run for each combination of effluent volume and standard concentration. For a 5% effluent volume, the introduction of discharge limits did not alter the composition of the optimal plans of production regardless of the type of standards, as compared to the model run including low-water exchange activities (Table 10). This indicates that semi-intensive shrimp farms in Honduras easily meet both GAA initial and target standard concentrations for TP and BOD_5 during routine water exchange. However, when the discharge limits were restricted based on an effluent quantity equal to 2% of total farm volume, the mathematical model introduced modifications in the plans of activities to meet the discharge limits at the target concentrations. It must be noted that limits were exceeded in this case because of the relatively high volume of farm effluent, not because of effluent concentration. It is also noteworthy that farms have the ability to meet discharge requirements with an effluent volume of 2% and initial standard concentrations even when actual water exchange rate is 5%.

Table 13 presents the calculated daily net discharges of TP and BOD_5 at 10 specific weeks in the production year (Weeks 13, 17, 21, 25, 30, 31, 39, 41, 45 and 49) associated with the optimal plans of production outlined in Table 10. Table 13 illustrates why changes in management strategies are only required when the most restrictive discharge limits are in place. Average net discharge of TP during the rainy season production cycles is 1.90, 11.56, and 38.56 kg/day/farm. Assuming a target standard of 0.3 mg/l and a 2% allowed effluent volume, TP net discharge limits are 1.61, 6.45, and 21.25 kg/day/farm for the small, medium, and large farms, respectively (Table 12). All other discharge limits, however, are complied with throughout the production year. On the other hand, none of the discharge limits specified for BOD_5 is exceeded at any week of the year.

Table 12. Net discharge limits (kg/day/farm) for TP and BOD_5 defined in the economic optimization model for shrimp farming in Honduras. Allowable discharge amounts represent the net quantities of TP and BOD_5 that can be released from ponds during water exchange without raising effluent concentration above the GAA standards, given a pre-determined volume of effluent. Assumed initial concentrations of TP and BOD_5 in the source water were 0.19 mg/l and 6.6 mg/l, respectively.

Farm-size scenario	**TP (kg/day/farm)**				**BOD_5 (kg/day/farm)**			
	5% pond volume		**2% pond volume**		**5% pond volume**		**2% pond volume**	
	Initial standard (5 mg/l)	Target standard (3 mg/l)	Initial standard (5 mg/l)	Target standard (3 mg/l)	Initial standard (50 mg/l)	Target standard (30 mg/l)	Initial standard (50 mg/l)	Target standard (30 mg/l)
Small farms (73 ha)	11.32	4.02	4.53	1.61	1,584.10	854.10	633.64	341.64
Medium farms (293 ha)	42.42	16.12	18.17	6.45	6,358.10	3,428.10	2,543.24	1,371.24
Large farms (966 ha)	149.73	53.13	59.89	21.25	20,962.20	11,302.20	8,384.88	4,520.88

Table 13. Estimates of TP and BOD_5 net discharges by water exchange (kg/day/farm) at 10 different weeks in the production year assuming farms are managed according to the optimal plans of production outlined in Table 10. Water exchange rate is 5%.

Week number (actual month in calendar year)	**TP (kg/day/farm)**			**BOD_5 (kg/day/farm)**		
	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)
13 (December)	0.59	3.45	11.57	41.49	241.34	809.27
17 (January)	0.66	3.45	11.57	46.32	241.34	809.27
21 (February)	0.69	3.63	12.08	48.33	253.70	844.65
25 (March)	0.83	2.67	8.72	58.27	186.30	608.75
30 (April)	0.93	2.67	8.72	65.18	186.30	608.75
31 (May)	0.93	2.67	8.72	65.18	186.30	608.75
39 (June)	1.96	11.56	38.56	137.41	809.50	2,700.61
41 (July)	1.92	11.56	38.56	134.96	809.50	2,700.61
45 (August)	1.86	11.56	38.56	130.13	809.50	2,700.61
49 (September)	1.86	11.56	38.56	130.13	809.50	2,700.61

Modifications in the optimal plans of activities required to meet the most restrictive TP discharge limits (0.3 mg/l TP, 2% water exchange rate, initial TP concentration of 0.19 mg/l) are presented in Table 14. The primary change across all farm-size scenarios is a reduction in the number of hectares allocated to the 15-PL/m^2 June activity with a resulting increase in the number of hectares stocked in July at 5 PL/m^2. As the expected pond yield for the June cycle is the highest in the year, stocking fewer hectares in June brings net discharges of TP by water exchange to levels sufficiently low to comply with the discharge requirements. Reducing pond area allocated to the June activity also leads to a net increase in the number of hectares allocated to the 15-week March cycle, i.e., a greater proportion of March hectares can be harvested at week 15 rather than at week 11. This occurs because the 15-week March cycles extend long enough to overlap with the June cycles. No changes were introduced during the dry season because production levels are sufficiently low so as not to exceed discharge requirements.

The net decrease in production levels during the rainy season brought about a reduction in net returns/ha above the most important variable costs of 4, 10, and 11% for the small, medium, and large farms, respectively, as compared to the base scenario of low water exchange rates presented in Table 10. Net returns/ha above total costs decreased to US$ 1,353; US$ 2,996 and US$ 3,719, respectively. These are significant reductions in farm profitability if one takes into consideration those modifications were caused by excess of farm effluent volume rather than of nutrient concentration in the effluent. Although current BMPs recommend lowering water exchange rates to the minimum practical levels, no specific recommendation has been formulated in terms of a maximum acceptable level or frequency of exchange. As mentioned before, some farms require routine water exchange to maintain a desired salinity range in ponds, and there is little the farm manager can do to improve this.

Table 14. Summary of production activities selected in the resolution of the LP model for shrimp farming in Honduras after imposing the most restrictive discharge limits of TP by water exchange (1.61, 6.45, and 21.25 kg/day/farm for the small, medium, and large farms, respectively). Discharge limits were calculated based on the GAA target standard for TP (0.3 mg/l), a quantity of effluent equivalent to a 2% water exchange rate, and an initial TP concentration of 0.19 mg/l.

Production activities				**Number of allocated ha**			**Expected tail count (no./lb)**
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	Low rate	10			71-90
October	12	15	Low rate	32			61-70
November	20	11	Low rate		93	266	71-90
November	20	15	Low rate	25	200	700	61-70
January	12	11	Low rate	16			71-90
February	20	15	Low rate	15	93	266	61-70
March	12	11	Low rate	12	22	113	61-70
March	12	15	Low rate	30	178	587	51-60
April	15	13	Low rate	16			51-60
June	15	21	Low rate	23	93	307	41-50
July	5	21	Low rate	34	200	659	31-35
August	5	21	Low rate	16			41-50
Net income/ha over selected variable costs (US$)				4,031	5,019	5,467	
Net income/ha above total costs (US$)				1,353	2,996	3,719	

Table 15 presents total and net TN, TP, and BOD_5 discharges for each farm size scenario resulting from reduced production levels. On average, TN, TP, and BOD_5 decreased by 22, 44, and 52% relative to the scenario of high water exchange rates (Table 9) and 8, 11, and 14% when compared to the low-water-exchange scenario (Table 11).

An important point to bear in mind is that the ability to meet discharge requirements based on standard recommendations is heavily dependent on the natural nutrient concentrations in the water supply (which may be in turn affected by other human activities). This analysis assumed an initial TP concentration of 0.19 mg/l; however, natural TP concentrations are higher for farms located farther upstream in the estuaries. There might be also drastic variations according to the climatic season. Green et al. (2000) reported an annual average TP concentration of 0.25 mg/l for El Pedregal estuary, which is the water source for several shrimp farms in the region. Table 16 presents the results of the LP model assuming a TP discharge requirement based on a target standard of 0.3 mg/l, a total effluent volume equivalent to a 2% water exchange rate, and an initial TP concentration of 0.25 mg/l. Net returns/ha over the most important variable costs decreased to US$ 3,373; US$ 4,240 and US$ 4,590 for the small, medium and large farms, respectively, a decrease of 20, 24, and 26% with respect to the baseline results of Table 10. Important changes in management strategies were needed to comply with the discharge requirements. Assuming that the farmer operates at a 5% water exchange rate, the June cycle must be dropped altogether and stocking densities must be reduced in the dry season (From 20 PL/m^2 in February to 12 PL/m^2 either in January or March). As the June cycle is dropped, a significant portion of farm area remains out of production in this month. Clearly, development of effluent standards needs to take into consideration all these spatial and temporal variations under which shrimp farming occurs to achieve rational goals for environmental management.

Table 15. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 5%. Water exchange discharge limits for TP and BOD_5 based on target standards and an effluent volume equivalent to a 2% exchange rate were included in the model simulation. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD_5**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	47.39	20.46	7.27	1.39	272.72	68.47	30,948
Medium farms (293 ha)	189.84	84.18	28.83	5.75	1,093.53	291.98	121,447
Large farms (966 ha)	625.53	277.18	95.02	18.95	3,603.70	961.02	400,405

Although net discharge limits for pond drainage were not developed in this study, the first 80-90% of drainage effluents appears to satisfy both initial and target standards for TP and BOD_5. Teichert-Coddington et al. (2000) reported average TP and BOD_5 concentration of 0.20 and 8 mg/l, respectively, for the first 90% of pond drainage effluent. Average concentration of TP during the last 10% portion of effluent did increase over 0.4 mg/l due to agitation of the pond bottom. This spike in concentrations can be attenuated by adherence to good pond construction practices or by circulation through a sedimentation basin prior to final release.

Improved Feed Management Through Feed Trays

The use of feed trays to apply or monitor feed consumption is a simple management tool that has improved feeding efficiency and reduced costs of production in several shrimp-growing countries, including Peru, Guatemala, and others (Viacava 1995; Jory and Dugger 2001). Teichert-Coddington et al. (2000) and Boyd et al. (2001) recommended the use of feed trays as a means to improve production efficiency on Honduran shrimp farms. Feed trays can be used strictly as indicators of feed consumption or as the primary technique for food dispersal in ponds. Although reportedly there is at least one farm in Honduras that applies 100% of the feed on trays, most farm managers distribute feed by boat over the pond surface (Boyd et al. 2001).

Table 16. Summary of production activities selected in the resolution of the LP model for shrimp farming in Honduras after imposing restrictions in net discharges of TP by water exchange (0.73, 2.93, and 9.66 kg/day/farm for the small, medium, and large farms, respectively). Discharge limits were calculated based on the GAA target standard for TP (0.3 mg/l), a quantity of effluent equivalent to a 2% water exchange rate, and an initial TP concentration of 0.25 mg/l.

Production activities				**Number of allocated ha**			**Expected tail count (no./lb)**
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	Low rate	19			71-90
October	12	15	Low rate	22			61-70
November	20	11	Low rate		200	664	71-90
November	20	15	Low rate	25	92	302	61-70
January	12	11	Low rate	26			71-90
February	12	11	Low rate		6		71-90
February	20	15	Low rate	6			61-70
March	12	11	Low rate	42	200	687	61-70
March	12	15	Low rate		87	279	51-60
April	5	13	Low rate	3			41-50
April	15	13	Low rate	21			51-60
July	5	17	Low rate		200	686	36-40
July	5	21	Low rate	49	91	280	31-35
August	5	21	Low rate	24			41-50
Net income/ha over selected variable costs (US$)				3,373	4,240	4,590	
Net income/ha above total costs (US$)				695	2,217	2,841	

The lack of widespread use of feed trays in Honduras is probably related to the scarcity of specific, country-related information on the cost-effectiveness of this method. Palmese et al. (2001) conducted the only known study in Honduras on the feasibility of trays as a feed distribution method as compared to the traditional dispersal of feed by boat. They carried out a replicated experiment on a commercial shrimp farm during both seasons, and found that FCRs could be improved on average by 33% during the rainy season (from 1.5 to 1.0) and by 64% during the dry season (From 2.8 to 1.0). A partial budget analysis was conducted for a cost comparison of both systems, and it was found that feed distribution by trays would bring about a 22% reduction in feed-related costs.

Information from the Palmese et al. (2001) study was adapted to make assumptions on the use of trays as the exclusive method of feed dispersal in the mathematical model. Improved FCRs resulting from the use of feed trays would increase profit margins while reducing net discharges of nutrients. Additional and reduced costs associated with feed trays were also factored in, as suggested by Palmese et al. (2001). Additional costs included the costs of trays and poles, as well as increases in labor costs to ensure proper feed distribution and monitoring. Reduced costs came in the form of reduced boat usage.

Although Palmese et al. (2001) report an impressive percentagewise reduction in FCRs, it was hypothesized that original FCR values (from the production records) of 1.0 or less were unlikely to be further improved. Based on the Palmese et al. (2001) findings, the following criteria were used for FCR improvement:

During the dry season

For original FCR values that were…	*A new FCR was calculated as…*
2.78	36% of the original value
Between 1.0 and 2.78	1.0
<1.0	The same original value

During the rainy season

For original FCR values that were…	*A new FCR was calculated as…*
1.49	67% of the original value
Between 1.0 and 1.49	1.0
<1.0	The same original value

Table 17 presents estimated FCRs for nine production activities under both scenarios of feed dispersal by boat and by feed trays. The most significant improvements in FCRs are achieved during the dry season. Table 18 presents the results of the mathematical model with the new FCRs. A significant increase in net returns/ha above the most important variable costs was observed, particularly for the small farms. Net returns/ha were US$ 4,756; US$ 6,005 and US$ 6,466 for the small, medium, and large farms, respectively, up 13, 8, and 5% with respect to the baseline results of Table 10. While no changes in optimal management strategies were recorded for the medium and large farms, the number of hectares allocated to the 21-week July, 15-week March, and 15-week October cycles was increased in the small farms. This resulted in a net decrease in number of hectares assigned to the 13-week cycle in April, and the 11-week cycles in March and January. The 11-week October cycle was excluded from the solution. As observed previously when water exchange rates were decreased from 10 to 5%, improvements in FCR increased the profitability of long production cycles relative to shorter ones, driving the model to extend the length of growout cycles to 15 weeks in the dry season and to 21 weeks in the rainy season.

Table 19 presents the estimated daily averages of total and net discharges of TN, TP, and BOD_5 for the three farm-size scenarios. Assuming that results obtained by Palmese et al. (2001) can be replicated on a commercial scale, net discharges of TN, TP, and BOD_5 would be reduced on average by 16, 19 and 25% in relation to the discharges obtained with the traditional method of feed dispersal (By boat) (Table 11). These substantial reductions in net nutrient loads become even more significant if the accompanying reduction in feed operational costs is also recognized. Another important result is that the technology of feed trays leads to lower average levels of net discharge as compared to those obtained by enforcing restrictive discharge limits (Table 15). Net discharges of TN, TP, and BOD_5 in the feed-tray scenario were on average 9, 9, and 12% lower.

Table 17. Feed Conversion Ratios (FCRs) for nine production activities assuming two feed distribution methods: by boat and by feed trays.

Weeks	FCR	
	Dispersal by boat	Dispersal by feed tray
October 5 PL/m²		
11	1.59	1.00
15	2.13	1.00
19	2.78	1.00
April 15 PL/m²		
13	1.03	1.00
17	1.36	1.00
21	1.74	1.17
June 25 PL/m²		
13	1.15	1.00
17	1.51	1.01
21	1.94	1.30

Table 18. Summary of production activities selected in the resolution of the economic optimization model for shrimp farming in Honduras assuming improvements in FCRs resulting from the use of feed trays as the exclusive method of feed distribution. No discharge limits were considered.

Production activities				Number of allocated ha			Expected tail count (no./lb)
Stocking month	Stocking rate (PL/m²)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	15	Low rate	42			61-70
November	20	11	Low rate		93	266	71-90
November	20	15	Low rate	25	200	700	61-70
January	12	11	Low rate	6			71-90
February	20	11	Low rate		93	266	71-90
February	20	15	Low rate	25			61-70
March	12	11	Low rate	8	200	700	61-70
March	12	15	Low rate	33			51-60
April	15	13	Low rate	6			51-60
June	15	17	Low rate		93	266	41-50
June	15	21	Low rate	33	200	700	41-50
July	5	21	Low rate	33			31-35
August	5	21	Low rate	6			41-50
Net income/ha over selected variable costs (US$)				4,756	6,005	6,466	
Net income/ha above total costs (US$)				2,078	3,982	4,718	

Table 19. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 5%. Feed distribution method is feed trays. No discharge limits were assumed. Total nutrient discharge refers to the total quantity of nutrients released from ponds (Including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD_5**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	44.30	17.91	6.97	1.20	257.66	56.82	30,340
Medium farms (293 ha)	172.62	77.38	26.13	5.32	984.50	261.93	109,479
Large farms (966 ha)	572.81	256.47	86.80	17.72	3,274.96	875.09	363,616

Table 20. Summary of production activities selected in the resolution of the LP model for shrimp farming in Honduras assuming improvements in FCRs resulting from the use of feed trays as the exclusive method of feed distribution. A discharge limit for TP (1.61, 6.45 and 21.25 kg/day/farm for the small, medium, and large farms) calculated upon the GAA target standard of 0.3 mg/l and a quantity of effluent equivalent to a 2% exchange rate was enforced.

Production activities				**Number of allocated ha**			**Expected tail count (no./lb)**
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	15	Low rate	42			61-70
November	20	11	Low rate		93	266	71-90
November	20	15	Low rate	25	200	700	61-70
January	12	11	Low rate	6			71-90
February	20	11	Low rate				71-90
February	20	15	Low rate	25	93	266	61-70
March	12	11	Low rate	8	107	422	61-70
March	12	15	Low rate	33	93	278	51-60
April	15	13	Low rate	6			51-60
June	15	17	Low rate				41-50
June	15	21	Low rate	33	188	631	41-50
July	5	21	Low rate	33	105	335	31-35
August	5	21	Low rate	6			41-50
Net income/ha over selected variable costs (US$)				4,756	5,865	6,254	
Net income/ha above total costs (US$)				2,078	3,842	4,506	

An additional model simulation was run to examine the effects of TP and BOD_5 discharge limits on the feed-tray scenario (Table 20). Because of the great reduction in average daily net discharges evidenced in Table 19, it was expected that imposing discharge limits would cause no modifications in the optimal mixes of activities shown in Table 18. However, some changes were indicated for the medium and large farm scenarios. Namely, the 17-week June cycle (15 PL/m^2) was replaced by a 21-week July cycle (5 PL/m^2) in order to meet discharge requirements during the rainy season. Also, fewer hectares were allocated to the 21-week June cycle. These changes led to extended February and March cycles (From 11 to 15 weeks) while no modifications were made during the dry season (November cycles). Net returns/ha above the most important variable costs decreased 2 and 3% for the medium and large farms, with respect to the previous discharge-free feed tray scenario. Changes occurred because feed trays are most effective in lowering net nutrient discharges during the dry season. Although nutrient discharges are still reduced during the rainy season, TP discharge limits may eventually be exceeded. Thus, average daily net discharges of TP in the feed tray scenario are lower than those produced in the discharge-restricted scenario of traditional feed dispersal (Table 15), but discharge limitations may still be exceeded at certain weeks of the rainy season.

Using Settling Basins to Reduce the Impact of Drainage Effluents

Diversion of effluents through settling basins before final release has been promoted by some as an effective means to reduce total nutrient loadings from aquaculture systems. Because some studies (Schwartz and Boyd 1994; Teichert-Coddington et al. 2000) have demonstrated that the last 10 to 15% of water discharged from ponds during drainage has a much higher concentration of nutrients, organic matter, and suspended solids than water released earlier, sedimentation of the last 10-20% of the pond volume is recommended to restore concentrations to pre-drainage levels (Boyd et al. 2001). Required hydraulic residence times may vary according to a host of factors such as design of the sediment basin and particle-size composition of the suspended solids in the effluent water; however, Boyd et al. (1998) suggest that pond effluent quality can be greatly improved with a six-hour retention time.

Many farm managers in Honduras feel that retrofitting existing drainage systems of farms to accommodate a sedimentation basin would be unfeasible mostly because of lack of land on which to install the basin (Boyd et al. 2001). Nevertheless, the Honduran government currently requires all new farm projects and proposals for expansion of existing firms to include a sedimentation treatment facility of approximately 10% the size of the new pond area in the construction plans (J. Romero, personal communication). As such, construction costs and nutrient removal capabilities of settling basins were estimated for the three farm-size scenarios on the assumption that sufficient land exists for basin installation.

Boyd et al. (1998) and Jones et al. (2001) performed laboratory studies while Teichert-Coddington et al. (1999) conducted a field trial to evaluate the potential of sedimentation for improving pond effluents. The latter two studies were conducted with effluents from shrimp ponds. In general, removal of nitrogen by settling appears less effective than for other nutrients, primarily because nitrogen tends to be more associated with phytoplankton and bacteria rather than readily settleable inorganic particles or detritus. Within a residence time of 24 h or less, removal rates for TP were 75% (Boyd et al. 1998), 55% (Teichert-Coddington et al. 1999), and 53% (Jones et al. 2001). Removal rates for TN were 31% (Teichert-Coddington et al. 1999) and 30% (Jones et al. 2001). Reported removal rates for BOD were 40% (Boyd et al. 1998) and 63% (Teichert-Coddington et al. 1999).

The efficiency of nutrient removal by settling is also dependent on the initial nutrient concentration. Initial TP concentrations in the three mentioned studies were 1.5, 1.16, and 0.65 mg/l, respectively. Initial TN concentrations were 4.35 and 4.06 mg/l, while initial BOD concentrations were 40 and 45 mg/l. In comparison, average TP, TN and BOD_5 concentrations during the first 90% of drainage effluent from Honduran shrimp farms were only 0.25, 2 and 8 mg/l, respectively (Teichert-Coddington et al. 2000). However, spikes in concentrations during the last 10% of effluent were reported for TP and TN (concentrations increased to 0.45 and 3.5 mg/l, respectively). As such, removal by settling appears practical for the treatment of only the last 10% of effluent drainage on Honduran farms. Therefore, a settling basin with a size equal to 10% of the pond area should be sufficient for the total volume of effluents from the farm.

Teichert-Coddington et al. (2000) reported an average TP net discharge during pond drainage of 1.0 kg/ha (Table 6b). Assuming an initial concentration of 0.19 mg/l, average TP concentration over all stages of volume effluent would be equal to 0.29 mg/l (0.29 – 0.19 mg/l = 0.10 mg/l = 1.0 kg/ha assuming pond depth is 1.0 m). Teichert-Coddington et al. (1999) stated that sedimentation of TP was complete after 6h of settling, i.e., high TP concentrations in the last 10% of effluent were restored to initial concentrations in the full pond prior to harvest. It was then assumed that sedimentation of the last 10% of effluent volume on Honduran farms would restore TP concentration from 0.45 mg/l to 0.25 mg/l (a 44% reduction), resulting in a final average TP concentration of 0.25 mg/l over all stages of effluent (down from the initial average of 0.29 mg/l). Net discharge of TP during pond drainage would then decrease from 1.0 to 0.6 kg/ha (0.25 mg/l – 0.19 mg/l = 0.06 mg/l = 0.6 kg/ha).

A similar approach was used to estimate reductions in net discharge of TN during pond drainage. Teichert-Coddington et al. (1999) estimated a 31% reduction in TN concentration during the final 20 cm of pond discharge, which corresponded to an overall 7% decrease for the full pond (1 m deep). Average TN discharge during pond drainage in Honduras is 9.7 kg/ha (Teichert-Coddington et al. 2000) which corresponds to an approximate concentration of 1.84 mg/l over all effluent stages, assuming an initial concentration of 0.87 mg/l in the source water. A 7% reduction in TN concentration for the full pond effected by sedimentation would result in a final TN concentration of 1.71 mg/l. Net discharge of TN during pond drainage would then fall from 9.7 to 8.4 kg/ha (1.71 mg/l – 0.87 mg/l = 0.84 mg/l = 8.4 kg/ha).

Sedimentation was not assumed to significantly reduce net discharges of BOD_5 because concentrations reported in Honduran effluents are rather low (8 mg/l on average) and remain constant through all phases of draining (Teichert-Coddington et al. 2000). In addition, Teichert-Coddington et al. (1999) revealed that BOD removal by settling was effective for 6 h, but thereafter BOD concentration increased again, probably because of autochthonous algal production in the settling basin.

Reductions in net discharges of TN and TP by pond drainage were used to re-estimate total net discharges for each production activity in the model. Table 21 provides a comparison of estimated net discharges under both scenarios of no treatment and treatment by sedimentation.

Engineering contractors were consulted in Honduras to obtain estimates of construction costs of settling basins for the three farm-size scenarios (Table 22). Given that layout of drainage systems may vary among farms and that larger farms tend to have more than one point of discharge, it was assumed that one, two, and four basins would have to be constructed for the small, medium, and large farms, respectively. As the required sedimentation area is 10% of farm size and basins within the same farm were assumed to be the same size, constructed basins had an area of 7.30 ha (small farms), 15 ha (medium farms), and 25 ha (large farms). Construction costs include earthmoving work and the construction of intake canals and discharge structures.

Table 21. Estimated net discharges of TN and TP by water exchange and pond drainage under two scenarios of no treatment and treatment of pond drainage effluents by sedimentation. Estimates are presented for nine production activities defined in the economic optimization model for shrimp farming in Honduras.

Length of growout cycle (wk)	TN (kg/ha)						TP (kg/ha)					
	No treatment			Treatment by sedimentation			No treatment			Treatment by sedimentation		
	Net loss by water exchange	Net loss by pond drainage	Total net loss	Net loss by water exchange	Net loss by pond drainage	Total net loss	Net loss by water exchange	Net loss by pond drainage	Total net loss	Net loss by water exchange	Net loss by pond drainage	Total net loss
Production cycles of varying lengths stocked in October at 5 PL/m^2. High water exchange rates (10%).												
11	11.2	9.7	20.9	11.2	8.4	19.6	0.17	1.0	1.17	0.17	0.6	0.77
15	16.9	9.7	26.6	16.9	8.4	25.3	0.39	1.0	1.39	0.39	0.6	0.99
19	22.7	9.7	32.4	22.7	8.4	31.1	0.71	1.0	1.71	0.71	0.6	1.31
Production cycles of varying lengths stocked in April at 15 PL/m^2. Low water exchange rates (5%).												
13	19.8	9.7	29.5	19.8	8.4	28.2	0.77	1.0	1.77	0.77	0.6	1.37
17	28.9	9.7	38.6	28.9	8.4	37.3	1.60	1.0	2.60	1.60	0.6	2.20
21	38.3	9.7	48.0	38.3	8.4	46.7	2.76	1.0	3.76	2.76	0.6	3.36
Production cycles of varying lengths stocked in July at 25 PL/m^2. High water exchange rates (10%).												
13	31.5	9.7	41.2	31.5	8.4	39.9	2.19	1.0	3.19	2.19	0.6	2.79
17	45.0	9.7	54.7	45.0	8.4	53.4	4.44	1.0	5.44	4.44	0.6	5.04
21	59.4	9.7	69.1	59.4	8.4	67.8	7.63	1.0	8.63	7.63	0.6	8.23

Table 22. Construction and annual amortized costs of settling basins for three farm-size scenarios of shrimp farms in Honduras. Required sedimentation area is approximately 10% of total pond area. Amortized annual costs were based on a 5-year loan in Lempiras at an interest rate of 25%. 2001 exchange rate = 1 US Dollar : 15.30 Lempiras.

Item	**Small farms (73 ha)**	**Medium farms (293 ha)**	**Large farms (966 ha)**
Sedimentation area (ha)	7.30	30.00	100.00
No. of basins	1	2	4
Topography cost (1 month)	1,954	1,954	1,954
Construction costs per basin			
Earthmoving			
Perimeter (m)	1,235.17	2,538.03	4,230.05
Unit volume (m^3)	8.97	8.97	8.97
Total volume (m^3)	11,079.47	22,766.13	37,943.55
Earthmoving rate (m^3/hr)	60.00	60.00	60.00
Number of tractors	3.00	4.00	4.00
Total earthmoving rate (m^3/hr)	180.00	240.00	240.00
Time (hours)	61.55	94.86	158.10
Average cost (US$/hr-mach.)	43.01	43.01	43.01
No. of hours-machine	184.66	379.44	632.39
Total earthmoving cost	7,942.95	16,321.18	27,201.97
Intake canal cost			
Length (m)	500.00	500.00	500.00
Unit volume (m^3)	12.00	12.00	12.00
Total volume (m^3)	6,000.00	6,000.00	6,000.00
Earthmoving rate (m^3/hour)	80.00	80.00	80.00
Number of machines	1.00	1.00	1.00
Total earthmoving rate (m^3/hour)	80.00	80.00	80.00
Time (hours)	75.00	75.00	75.00
Average cost (US$/hourr-mach.)	47.35	47.35	47.35
Total intake-canal cost	3,551.47	3,551.47	3,551.47
Discharge structures			
Structure cost	8,434.95	8,434.95	8,434.95
Total cost per basin	21,883.62	30,261.86	41,142.64
Total cost of project (US$)	21,883.62	58,569.46	158,707.83
Amortized annual costs (US$)	8,137.35	21,778.86	59,014.99

The total cost of the project was calculated as the construction cost per basin times the number of basins, plus an additional topography cost. Annual amortization tables were developed for each budgeted amount on the assumption that a 5-year loan would be made in Lempiras (Honduras currency) at a 25% annual interest rate. The annual amortized costs (converted to US Dollars) were US$ 8,137; US$ 21,779 and US$ 59,015 for the small, medium, and large farms (Table 22). These costs were added to the structure of fixed costs shown in Table 5.

Because it is treated as a fixed cost, constructing settling basins does not have an impact on net returns above variable costs, but it affects the farm's ability to meet cash flow requirements. Although not mentioned previously, the mathematical model also contains a financial component that determines the borrowing needs of the farm based on the availability of cash from shrimp sales. Through a series of cash flow constraints, this financial component requires that a minimum amount of cash be generated every four-five weeks by harvesting ponds, using the savings from previous harvests, or borrowing funds. This cash is then used to cover a wide range of farm expenses such as payroll, equipment and pond repairs, security, etc. The annual amortized cost of settling basins was added to the cash flow requirement of week 61, when cash would be available from the 21-week June cycles. In the baseline scenario, cash flow requirement in week 61 is US$ 16,289; US$ 49,395 and US$ 140,730 for the small, medium, and large farms. These amounts increased to US$ 24,426; US$ 71,174 and US$ 199,745, respectively, in the settling basin scenario. In addition to increasing annual fixed costs, constructing settling basins may potentially introduce modifications to the optimal mixes of production activities driven by the additional cash flow requirement.

One problem with settling basins is that conflicts in harvesting schedules are likely to arise if a large number of ponds is to be harvested in a relatively short period of time, even when short residence times are used (24 hours or less). To examine this impact, a set of stocking requirements were defined within the model to force it to initiate production cycles every month of the production year on at least 15% of the pond area on the farm. These requirements resulted in a more continuous pattern of stocking and harvesting activities throughout the year, ensuring a more regular use of settling basins within the farm. This type of scenario is more similar to farms that are required by processing plants to deliver farm produce on a regular basis. These farms are not able to take advantage of the higher profits that can be obtained by stocking and harvesting in production blocks.

Table 23 presents the results of the LP model assuming a continuous production schedule prior to settling basin installation. Net returns above the most important variable costs were US$ 3,206; US$ 4,786 and US$ 5,187 for the small, medium, and large farms, respectively; down 24, 14 and 16% with respect to the baseline scenario of production in blocks (Table 10). Clearly, monthly stocking requirements result in dramatic decreases in farm profit margins, especially for the small farms. Net returns/ha above all costs of production decreased to US$ 528 in this farm scenario. Production schedules for the medium and large farms continued to revolve around the November, March, and June cycles, with supplemental stocking conducted in the remaining months. More profound changes occurred in the small-farm scenario. The optimal plan called for a major production cycle early in the dry season (11-week October cycle). Production in the rainy season revolved around the April and August cycles rather than the March-June-July combination selected in the baseline scenario (Table 10). All these changes were primarily driven by a need to reduce borrowing levels at the beginning of the year (to satisfy the initial cash flow requirements). Under the baseline scenario, a sufficient number of hectares can be allocated to the most profitable cycles so as to afford borrowing at the beginning of the year; however, this ability disappears when monthly stocking requirements are enforced.

Table 24 presents the respective total and net discharge levels for TN, TP and BOD_5. Because overall annual yields are lower with the system of continuous production, net discharges for TN, TP and BOD_5 are on average 6, 9 and 14% lower than those produced under the baseline scenario of production in blocks (Tables 10 and 11).

Table 25 presents the results of the mathematical model after incorporating the amortized annual cost of settling basins. Relative to the previous scenario of staggered production, no changes were observed in the composition of the optimal mixes of activities while net returns/ha above the most important variable costs decreased by negligible amounts (Less than 1% on average). This slight decline was due to the additional cash flow requirement of week 61 that caused a reduction in the amounts of savings at the end of the year (Savings accumulated over the production year were assumed to earn an interest of 10% per year, which was added to net farm income). Fixed costs did increase by 4, 4, and 3% in the small, medium, and large farms, bringing net returns above all costs of production to US$ 411; US$ 2,687 and US$ 3,376 (A decrease of 22, 3 and 2%, respectively). In conclusion, the primary cost associated with settling basin installation in existing farms is not linked to direct construction costs (although fixed costs do increase by 4% on average), but to adjustments in the optimal production plans needed to harmonize pond draining schedules. Constructing settling basins is a relatively large expense for small farms that harvest regularly as profit margins of these operations are already narrow.

Finally, Table 26 indicates total and net discharges of TN, TP and BOD_5 for the settling basin scenario. Compared to the previous scenario (Table 24), net discharges for TN and TP were lower by 4 and 18%, respectively. No reductions in BOD_5 were assumed. Based on the reduction in net returns above all costs of production between the two scenarios, the costs of achieving a 1-kg reduction in net discharge of TN and TP were US$ 5,568/kg and US$ 23,640/kg. Compared to the baseline scenario of production in blocks (Tables 10 and 11), TN and TP net discharges were reduced on average by 10 and 25%. However, direct comparison between these two scenarios is not valid because they represent different levels of production.

Use of Mangrove Wetlands to Treat Pond Effluents

Constructed mangrove wetlands have received a great deal of attention recently because of their potential for effective removal of suspended solids and absorption of dissolved nutrients from shrimp pond effluents (Robertson and Phillips 1995; Massaut 1999; Rivera-Monroy et al. 1999; Boyd et al. 2001). Diversion of effluents through a mangrove biofilter would reduce nutrient loading through several physicochemical processes, including sedimentation of solids, plant uptake, and denitrification. Although a number of authors have reported the effectiveness of mangroves in removing nutrients from effluent waters (Corredor and Morell 1994; Wong et al. 1995; Avendaño-Remolina and Sánchez-Arias 1995), understanding of the recycling dynamics of the various forms of nitrogen and phosphorus nutrients within mangrove systems has just begun (Massaut 1999, Rivera-Monroy et al. 1999). Nevertheless, there is evidence that shrimp pond effluents can stimulate the biomass production of various mangrove species (Rajendran and Kathiresan 1996; Rivera-Monroy et al. 2001). Thus, the development of integrated shrimp farm-mangrove systems could achieve the twofold objective of effluent treatment and mangrove conservation in areas where mariculture is practiced.

Mangrove forests function as sinks of inorganic nitrogen (Rivera-Monroy and Twilley 1996) and phosphorus (Alongi 1996) in the coastal zone. Based on the high uptake rate of inorganic N for plant growth, Robertson and Phillips (1995) estimated that 2-22 ha of mangrove wetlands would

Table 23. Summary of production activities selected in the resolution of the economic optimization model for shrimp farming in Honduras. Two regimes of water exchange rates (high and low) were considered. A new stocking requirement specifying that at least 15% of farm area needs to be stocked every month was defined for each farm scenario.

Production activities				**Number of allocated ha**			**Expected tail count (no./lb)**
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	Low rate	33	40	140	71-90
October	12	15	Low rate	5			61-70
November	20	11	Low rate	5	40	140	71-90
November	20	15	Low rate	20	173	546	61-70
December	12	15	Low rate	10	40	140	61-70
January	12	11	Low rate	33	40	140	71-90
February	20	15	Low rate	10	40	140	61-70
March	12	11	Low rate		133	406	61-70
March	12	15	Low rate	10	40	140	51-60
March	12	19	Low rate	9			41-50
April	15	13	Low rate	33	40	140	51-60
May	15	13	Low rate	10	40	140	51-60
June	15	21	Low rate	10	173	546	41-50
July	5	21	Low rate	10	40	140	31-35
August	5	21	Low rate	43	40	140	41-50
September	5	17	Low rate	10	40	140	36-40
Net income/ha over selected variable costs (US$)				3,206	4,786	5,187	
Net income/ha above total costs (US$)				528	2,763	3,439	

be needed to remove the dissolved inorganic nitrogen loading from a 1-ha shrimp pond. Rivera-Monroy et al. (1999) demonstrated that this initial mangrove:pond area ratio was overestimated because nutrient losses due to denitrification, sedimentation, and soil absorption had not been accounted for. If denitrification were considered, 0.04-0.12 ha of mangrove would be sufficient to remove the dissolved inorganic nitrogen from the effluents of a 1-ha pond.

Sanchez-Arias et al. (2001); Gautier et al. (2001); and Gautier (2002) described and measured the actual removal efficiency of the only known integrated shrimp farm-mangrove forest system in the Western Hemisphere. This is a commercial shrimp farm built on former cattle lands on the Caribbean Coast of Colombia. A 120-ha mangrove wetland has been constructed to treat and recirculate the effluents of 235-ha of ponds. Although the system has resulted in spectacular removal levels for Total Suspended Solids (TSS), BOD and phytoplankton counts (The biofilter was initially designed to control populations of blue-green algae present in the supply water), Gautier et al. (2001) reported that concentrations of most dissolved nutrients (SRP, TAN and NO_3) in the pond effluent actually increased after passing through the biofilter, relative to the concentrations in the water supply and drainage canals. In the case of SRP, the increase in concentration was six-fold. This unexpected outcome was interpreted as the consequence of the production of guano by a large bird community (egrets, herons and other birds) that roosted in a section of the biofilter.

Table 24. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 5%. Monthly stocking requirements have been defined to enforce a pattern of continuous production throughout the year. No discharge limits were assumed. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD_5**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	47.88	19.90	7.41	1.30	271.49	59.24	32,159
Medium farms (293 ha)	191.91	88.10	28.86	6.19	1,104.94	317.42	119,321
Large farms (966 ha)	631.42	288.51	95.08	20.19	3,632.04	1,030.66	394,148

Despite the results reported by Gautier et al. (2001), integrated shrimp farm-mangrove forest systems do have potential to decrease dissolved nutrient concentrations. The Colombian case represents a typification of the many factors (Endogenous and exogenous) involved in the nutrient dynamics of such complex systems. Construction of mangrove biofilters is being considered in a current program of mangrove rehabilitation and integrative management with the shrimp aquaculture industry in Honduras (Rivera-Monroy et al. 2001). Although much information needs to be collected to assess the feasibility of such a system in its various aspects (Species composition, removal capabilities, engineering design, etc.), support of this integrated approach would demonstrate a high level of environmental stewardship on the part of the shrimp farming industry.

Shrimp-farm mangrove forest systems in Honduras need to be developed according to the particular characteristics of the industry. For instance, Rivera-Monroy et al. (1999) found that TAN concentrations in effluents from three semi-intensive shrimp farms in Colombia doubled those found in adjacent estuaries. However, Teichert-Coddington et al. (2000) reported that TAN, as well as nitrate and nitrite concentrations, are on average lower in the water exchange effluent than in the pond influent in Honduras. Effluent concentrations seem also to be lower during pond drainage, at least in the first 90% of effluent. As such, shrimp ponds in Honduras actually function as sinks of dissolved inorganic nitrogen. Apparently, there is also a net intake of SRP in unfertilized ponds. Gautier et al. (2001) and other authors have also reported cases of semi-intensive shrimp farms in which the concentration of dissolved nutrients is lower in the pond effluents than in the water source.

Table 25. Summary of production activities selected in the resolution of the LP model for shrimp farming in Honduras. Two regimes of water exchange rates (high and low) were considered. A new stocking requirement specifying that at least 15% of farm area needs to be stocked every month was defined for each farm scenario. The amortized annual costs of settling basins were included in the model simulation.

Production activities				Number of allocated ha			Expected tail count (no./lb)
Stocking month	Stocking rate (PL/m^2)	Length (weeks)	Water exchange regime	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	
October	12	11	Low rate	33	40	140	71-90
October	12	15	Low rate	5			61-70
November	20	11	Low rate	5	40	140	71-90
November	20	15	Low rate	20	173	546	61-70
December	12	15	Low rate	10	40	140	61-70
January	12	11	Low rate	33	40	140	71-90
February	20	15	Low rate	10	40	140	61-70
March	12	11	Low rate		133	406	61-70
March	12	15	Low rate	10	40	140	51-60
March	12	19	Low rate	9			41-50
April	15	13	Low rate	33	40	140	51-60
May	15	13	Low rate	10	40	140	51-60
June	15	21	Low rate	10	173	546	41-50
July	5	21	Low rate	10	40	140	31-35
August	5	21	Low rate	43	40	140	41-50
September	5	17	Low rate	10	40	140	36-40
Net income/ha over selected variable costs (US$)				3,200	4,784	5,186	
Net income/ha above total costs (US$)				411	2,687	3,376	

The effectiveness of mangrove biofilters on Honduras shrimp farms would lie in their ability to remove the remaining portion of TN (Dissolved organic nitrogen and particulate nitrogen) and TP (Mostly in the particulate form) that is being exported from the ponds. With the current state of knowledge, however, it is difficult to assess the true assimilation capabilities of mangrove forests with respect to these nutrient forms. Removal of the particulate fractions would be primarily related to the accumulation rates of N and P in mangrove soils. Dissolved organic and particulate nitrogen could also be removed by other mechanisms, such as coupled mineralization and denitrification. However, the potential contribution of these processes has not been evaluated yet (Rivera-Monroy et al. 1999).

Based on the limited information available, Rivera-Monroy et al. (2001) developed preliminary estimates of treatment capacities and mangrove forest area requirements for the largest shrimp farm in Honduras (2,965 ha). Figures 1 and 2 present the estimated potential nitrogen and phosphorus treatment capacities (kg/ha/day). Treatment capacities were calculated as the difference between total inputs and outputs, with a positive number indicating that the forest has an excess capacity for nutrient assimilation/utilization. Nitrogen gains include effluent loading, nitrogen fixation, and tidal inundation, while nitrogen losses occur through denitrification, plant uptake, and accumulation in soil. It is hypothesized that 30% of the TN loading could be accumulated in the soil.

Table 26. Annual estimates of average total and net discharge quantities of selected nutrients from Honduras shrimp farms managed without pond fertilization. Daily water exchange rate is 5%. Monthly stocking requirements have been defined to enforce a pattern of continuous production throughout the year. No discharge limits were assumed, but amortized annual costs of settling basin construction have been included. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation.

Farm-size scenario	**Variable (kg/day/farm)**						**Average discharge volume (m^3 water/day)**
	TN		**TP**		**BOD_5**		
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	
Small farms (73 ha)	46.92	18.94	7.13	1.02	271.49	59.24	32,159
Medium farms (293 ha)	188.38	84.58	27.85	5.18	1,104.94	317.42	119,321
Large farms (966 ha)	619.77	276.86	91.75	16.86	3,632.04	1,030.66	394,148
Average cost of abatement (US$/kg)	5,568		23,640		-		-

Contingent upon mineralization rates, the remaining organic nitrogen present in the residual 70% would be transformed through denitrification and plant uptake processes. Phosphorus would enter the system in the effluent loading and be removed by plant uptake and accumulation in soil. It is not clear yet whether phosphorus would be imported or exported during tidal inundations. Effluent loadings correspond to the estimates presented in Table 11, which assume a daily water exchange rate of 5%. As concentrations of DIN and SRP do not increase in shrimp ponds, loadings were based on intake water concentrations reported by Teichert-Coddington (2000) for estuaries in Honduras (0.136 and 0.112 mg/l, respectively). The resulting effect is that both DIN and SRP concentrations at the biofilter outlet would be lower than those found in the water supply.

Table 27 presents area estimates for mangrove wetlands on small, medium, and large farms. Estimates were based on the wetland:pond area ratios developed by Rivera-Monroy et al. (2001). Ratios were calculated for each nutrient as the proportion between pond effluent loading and treatment capacity. The largest area requirement corresponded to TN (45% of farm area) as effluent loading was high relative to the estimated treatment capacity. The wetland: pond area ratio on the Colombian farm was 0.51, which is close to this study's estimate.

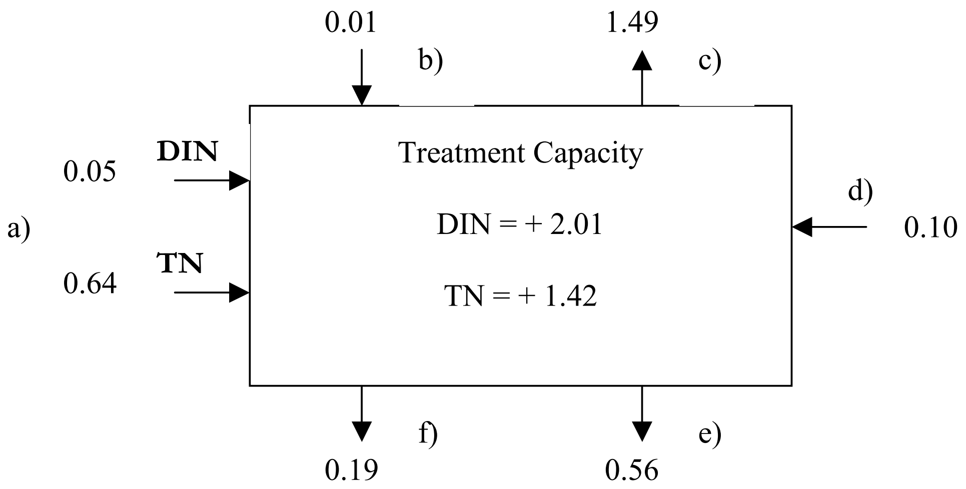

Figure 1. Estimated potential nitrogen treatment capacity (kg/ha/day) of a mangrove forest receiving effluents from shrimp aquaculture ponds in Honduras. DIN = dissolved inorganic nitrogen; TN = total nitrogen. a) pond effluent, b) nitrogen fixation, c) denitrification, d) tidal inundation, e) plant uptake, and f) N accumulation in soil. Nitrogen fluxes are from Rivera-Monroy et al. (1999) except pond effluent estimates (this study). Taken from Rivera-Monroy et al. (2001).

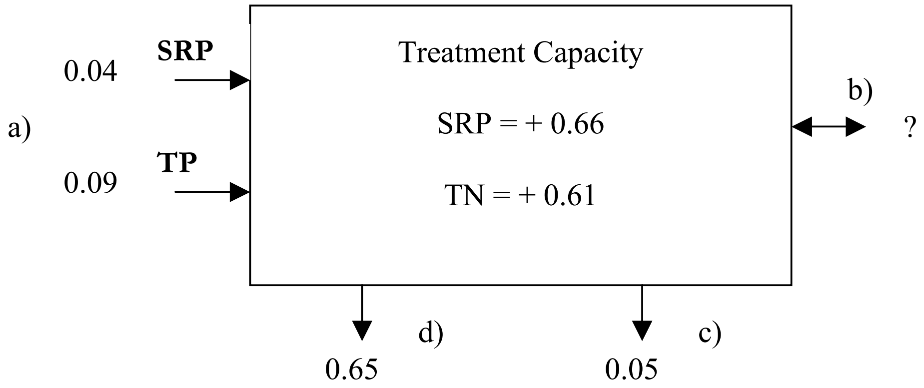

Figure 2. Estimated potential phosphorus treatment capacity (kg/ha/day) of mangrove forests receiving effluents from shrimp aquaculture ponds in Honduras. SRP = soluble reactive phosphorus; TP = total phosphorus. a) pond effluent (this study), b) tidal inundation, c) plant uptake (Robertson and Phillips 1995), and d) P accumulation in soil (Lynch 1989). Taken from Rivera-Monroy et al. (2001).

Assuming that sufficient land is available, preliminary construction costs of mangrove wetlands were estimated for each farm-size scenario assuming a 0.45 wetland: pond area ratio. Because no precise information is available for Honduras, construction and operational costs of the Colombian biofilter were taken as a reference. Drawing from the Colombian experience, it is clear that a distinction should be made between “natural” and “artificial” biofilter systems. Gautier (2002) reported that construction of the 120-ha biofilter cost about US$ 100,000 in 1995. At that time, the biofilter was fully operational but relatively few modifications had been made to the natural mangrove system serving as a biofilter. Since then, the Colombian shrimp farm has undertaken important infrastructure works to optimize flow and improve nutrient removal capabilities. As of 2000, total investment had escalated to approximately US$ 650,000 (L.E. Sánchez-Arias, personal communication). In view of the disparity in cost estimates and the uncertainty on the true costs of such a system, cost estimates were developed for Honduras based on “natural” and “artificial” mangrove systems. For a “natural” system, costs were assumed to be US$ 27,000, US$ 90,000 and US$ 285,000 for the small, medium, and large farms, respectively. This system assumes the existence of a mangrove forest of the proper size and characteristics located right behind the ponds. For a more elaborate, “artificial” system, total costs of construction and system setup were US$ 163,903, US$ 546,093 and US$ 1,727,665, respectively (Table 28). The artificial system implies a great deal of levee and road construction as well as stocking and maintenance of mangrove seedlings. Costs of the artificial biofilter are high if compared to the costs of settling basin construction (Table 22). However, it should be noted that these mangrove biofilters allow for partial or complete recirculation of effluents back into the production ponds, greatly reducing the impact of discharges. Gautier (2000) points out that the integrated system has represented enormous savings in effluent tax payments to the Colombian shrimp farm.

Another consideration is that construction of mangrove wetlands provides more than a simple mechanism for pond effluent treatment. This integrated system may represent an effective approach for the restoration of mangroves in deforested areas. Sánchez-Arias et al. (2001) reported that the integrated shrimp farm-mangrove system in Colombia has essentially become a refuge for migratory birds and endangered wildlife species. Rivera-Monroy et al. (2001) also promoted this integrated approach since constructed mangrove wetlands can provide a first-class learning environment for applied research on mangrove ecology and ecophysiology problems.

As was previously done in the settling basin analysis, annual amortized costs were estimated for the construction and setup of both natural and artificial mangrove biofilters based on 5-year loans in Lempiras at an annual interest rate of 25%. The annual amortized costs were added to the cash flow requirement of week 61 to ensure that funds from the harvested June cycles are available. Monthly stocking requirements were also included in the model simulation (as done previously with settling basins) to enforce a more regular schedule of pond harvests and a more consistent regime of inundation in the mangrove forest.

Table 29 presents the results of the mathematical programming model for both natural and artificial mangrove wetland scenarios. No changes in optimal management strategies in either scenario were observed relative to the baseline situation of regular pond harvesting (Table 23). Net returns/ha above the most important variable costs decreased slightly, but reductions in net returns above total costs were significant, especially for the small farms. The construction of mangroves resulted in continued borrowing throughout the year for the small farms as the annual amortized costs increased financial obligations to the point that cash flow requirements could not be met by pond harvesting. In the case of “artificial” mangroves, the annual amortized costs represented an average increase of 35% in fixed costs, which led to negative net returns/ha above all costs of production (-US$ 359) for the small farms. However, net returns/ha were positive across all farm scenarios when few modifications were required to install the biofilter (natural system).

Table 27. Potential treatment capacity and area requirements of mangrove forests for three farm-size scenarios in Honduras.

DIN			**TN**			**SRP**			**TP**		
Treatment capacity (kg/ha mangrove/ day)	Ratio wetland: pond area	Mangrove area needed (ha)	Treatment capacity (kg/ha mangrove/ day)	Ratio wetland: pond area	Mangrove area needed (ha)	Treatment capacity (kg/ha mangrove/ day)	Ratio wetland: pond area	Mangrove area needed (ha)	Treatment capacity (kg/ha mangrove/ day)	Ratio wetland :pond area	Mangrove area needed (ha)
Small farms (73 ha)											
2.01	0.03	1.9	1.42	0.45	33.2	0.66	0.06	4.7	0.61	0.15	11.3
Medium farms (293 ha)											
2.01	0.03	7.5	1.42	0.45	133.3	0.66	0.06	18.7	0.61	0.15	45.3
Large farms (966 ha)											
2.01	0.03	24.6	1.42	0.45	439.4	0.66	0.06	61.7	0.61	0.15	149.4

Table 28. Construction, annual amortized, and annual operational costs of mangrove forests for three farm-size scenarios of shrimp farms in Honduras. A mangrove: pond area ratio of 0.45 was assumed. Amortized annual costs were based on a 5-year loan in Lempiras at an interest rate of 25%. 2001 exchange rate = 1 US$: 15.30 Lempiras. Based on costs of a constructed mangrove wetland in Agrosoledad, Caribbean coast of Colombia (L.E. Sánchez-Arias, personal communication).

Item	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)
Mangrove forest area (ha)	33.2	133.3	439.4
Construction of biofilter (US$)			
Flow control structures	14,229	57,129	188,314
Walls	16,896	67,840	223,623
Roads and bridges	7,411	29,754	98,080
Channels	48,948	196,528	647,821
Drainage structures	22,084	88,668	292,279
Subtotal	109,567	439,920	1,450,118
System setup (US$)			
Technical consultancy	37,143	37,143	50,000
Seeding	12,450	49,988	164,775
Back-up system	4,743	19,043	62,771
Subtotal	54,336	106,173	277,546
Total cost of project (US$)	163,903	546,093	1,727,665
Amortized annual cost (US$)	60,947	203,063	642,426
Annual cost of operation (US$)	15,000	40,000	55,000

Overall, net returns above all costs of production decreased by 29, 4, and 3% with the natural biofilter and 168, 26, and 20% with the artificial system for the small, medium, and large farms, respectively.

No estimates of total and net discharges of TN, TP and BOD_5 are presented for either mangrove forest system because no sufficient data exist yet to indicate with precision the removal rates of nutrients. Theoretical calculations as well the results from Sánchez-Arias et al. (2001) and Gautier et al. (2001) suggest that removal rates could be high. In any case, the mangrove systems allow for partial recirculation of effluents, implying that the impact of discharges on the estuaries would be minimal.

Table 29. Results of the economic optimization model for the two mangrove-biofilter scenarios. Selected production activities are the same as those presented in Table 23 (baseline scenario). Net income above total costs includes the amortized costs of mangrove biofilter construction.

	"Natural" Mangrove Forest			"Artificial" Mangrove Forest		
	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)	Small farms (73 ha)	Medium farms (293 ha)	Large farms (966 ha)
Net income/ha above selected variable costs (US$)	3,192	4,783	5,184	3,154	4,769	5,170
Net income/ha above total costs (US$)	376	2,646	3,326	-359	2,053	2,757

Economic Analysis of Better Management Practices (BMPs) for Small Producers in Honduras and Shrimp Cooperatives in Nicaragua

A related analysis was conducted to evaluate the economic impact of BMPs on organizations of small shrimp producers in Honduras and Nicaragua. Information was collected during visits to both countries in August 2001. An association of small shrimp producers in Honduras provided production and financial data of recent production cycles. In Nicaragua, various reports on technical and financial assistance provided to shrimp farm cooperatives by the Centro de Investigación del Camarón (Shrimp Research Center) - Universidad Centroamericana (UCA) were consulted. Based on this information, an annual enterprise budget assuming two production cycles per year was developed for each country. The annual budgets were used as a benchmark to evaluate the economic and environmental effects of the following BMPs: 1) Reduction of water exchange rates from 10 to 5%; 2) Use of feed trays; 3) Construction of settling basins; and 4) Construction of a mangrove wetland.

Tables 30 and 31 present the production parameters and annual enterprise budget for a 26-ha artisanal shrimp farm in Honduras. It was assumed that most of the farm produce would be sold to a processing plant, with a small portion going to the local market. At an annual yield of 1,740 lb/ha and average shrimp price of US$ 2.77/lb, net returns/ha were US$ 483. Profit margins were strongly affected by low survival rates during the first cycle (25%), low shrimp prices for the second crop of the year (US$ 2.60/lb for 61-70 shrimp), and financial obligations. Tables 32 and 33 present the production assumptions and enterprise budget for an 85-ha shrimp cooperative in Nicaragua. The combination of low production levels (annual yield was less than 1,000 lb/ha) and a heavy financial burden resulted in net returns/ha of only US$ 129/ha. Shrimp cooperatives in Nicaragua depend almost exclusively on borrowed capital to build farm infrastructure and cover operating expenses. Consulted reports revealed that insufficient revenue is produced in some production cycles to meet the financial obligations of the respective period. As a result, some shrimp cooperatives have accumulated significant levels of debt. Financial stress in these farms is partially due to the widespread devastation caused by Hurricane Mitch in October 1998, which resulted in the loss of entire crops and extensive damages to farm infrastructure.

Table 30. Production assumptions used in the development of an annual enterprise budget for a 26-ha artisanal farm in Honduras.

Item	First production cycle (March – July)	Second production cycle (August - December)
Stocking density (PL/m^2)	19	15
Length of cycle (days)	120	120
Survival (%)	25	40
Weekly growth rate (g/week)	0.66	0.66
Harvest weight – whole shrimp (g)	11.36	11.36
Tail count (no./lb)	61-70	61-70
FCR	1.63	1.42
Water exchange rate (%)	11	11
Pond yield (lb of shrimp tails/ha)	763	977
Shrimp price (US$/lb of shrimp tail)	2.98	2.60

Tables 34 and 35 summarize the effect of the BMPs on annual net returns/ha for each farm scenario. Pond yields were assumed to remain unaffected by lower exchange rates while FCRs were lowered to 1.0 in each production cycle in the feed tray scenario. Costs of settling basin installation and construction of mangrove biofilters were based on the previous analysis of Honduran farms. Annual amortized costs were estimated on the same assumption of a 5-year loan in national currency.

Improved water and feed management through reduced water exchange and the use of feed trays resulted in increases in net returns/ha in both farm scenarios. Profit margins of small-scale shrimp farming in Central America are very low, thereby providing an extra incentive to improve production efficiency through the use of BMPs. For instance, records from the Honduran farm indicated that water is currently exchanged at an approximate rate of 11%, which appears to be excessive. Additionally, the reduced size of these operations makes the use of feed trays a feasible approach for feed distribution. The combined implementation of both BMPs (reduced water exchange and feed trays) led to an increase of over 80% in net returns/ha in each farm scenario.

Construction of treatment facilities (settling basins and mangrove wetlands) drastically reduced profit margins in both farms. As these operations are completely dependent on borrowed capital, construction of these facilities would increase financial obligations to unsustainable levels. Net returns/ha became negative in both farm scenarios after incorporating the annual amortized cost of artificial mangrove wetlands.

Tables 36 and 37 present estimates of total and net discharges of nutrients over the two cycles of production in both farms. The small-scale farm in Honduras reported use of fertilizers, thus total and net discharges of TP were increased according to the findings of Teichert-Coddington et al. (2000). The addition of fertilizers also resulted in a net discharge of SRP rather than pond intake (Table 36). No fertilizer use was assumed for the shrimp cooperative in Nicaragua, meaning that discharges of TP (on a per ha basis) were lower than those of the Honduran farm while SRP was retained in the pond rather than exported in the effluent. Results showed that the most effective reductions in net discharges of nutrients were achieved through the combination of low water exchange rates and feed dispersal through feed trays.

Table 31. Annual enterprise budget for a 26-ha artisanal shrimp farm in Honduras based on 2001 prices and costs. Two production cycles per year were assumed.

Item	Description	Unit	Quantity	Price/ unit (US$)	Total cost (US$)
Gross Returns					
Shrimp	Size 61-70	lb	45,246	2.77	125,121
Variable Costs					
Post-larvae (PL)	Wild	1,000	8,767	2.50	21,917
Feed	25% protein	hundredweight	1,052	23.53	24,753
Fertilizer		hundredweight	56	9.80	549
Labor		dollars			8,235
Diesel		dollars			7,701
Equipment repairs		dollars			2,092
Pond preparation		ha	21	39.00	825
Lime		hundredweight	800	1.70	1,359
Filters	Two / pond	filter	10	40.61	406
Trips		dollars			3,074
Office stationary		dollars			159
Ice		hundredweight	696	2.60	1,810
Interest on operating capital[a]	28% annual	dollars			3,345
Total variable costs (TVC)		dollars			76,225
Fixed Costs					
Debt payments		dollars			36,286
Concession		ha	30	1.31	39
Total fixed costs (TFC)		dollars			36,326
Total costs (TC)		dollars			112,551
Net returns		dollars			12,570
Net returns per unit area		dollars/ha			483
Breakeven price at 1,740 lb/ha		dollars/lb			2.49
Breakeven yield at US$2.77/lb		lb/ha/year			1,565

[a] Operating capital was borrowed only during the second cycle of the year.

Just by lowering water exchange rates from 11 to 5%, net discharge of nutrients can be decreased by 20-54% in the small-scale Honduran farm. Reduction of net discharges was more effective in the Honduran scenario due to the use of fertilizers. In contrast, settling basins achieved relatively low levels of nutrient removal except for TP in the Nicaraguan farm. This occurred because settling basins were primarily targeted at the treatment of the last 10% of drainage effluent; however, since these operations drain ponds only twice a year, the resulting effect is that basins remain under-utilized during most of the year. Sedimentation was relatively ineffective in reducing net discharges of TP in the Honduran farm because the use of fertilizers resulted in a much greater portion of TP being exported through water exchange. Therefore, a more efficient approach is simply to reduce levels of water exchange to allow a more complete assimilation of phosphorus within the pond.

Table 32. Production assumptions used in the development of an annual enterprise budget for an 85-ha shrimp cooperative in Nicaragua.

Item	First production cycle (May – September)	Second production cycle (October - January)
Stocking density (PL/m^2)	7	7
Length of cycle (days)	106	106
Survival (%)	38	30
Weekly growth rate (g/week)	0.85	0.75
Harvest weight – whole shrimp (g)	12.92	11.41
Tail count (no./lb)	51-60	61-70
FCR	1.50	1.80
Water exchange rate (%)	10	10
Pond yield (lb of shrimp tails/ha)	493	343
Shrimp price (US$/lb of shrimp tail)	2.80	2.60

No estimates of nutrient discharges are presented for the mangrove wetland scenarios given that little information exists on the actual removal capabilities of these systems. Potentially, mangrove wetlands could remove most of the nutrient loading in the effluent. In view of the high costs of a fully-developed mangrove biofilter, this technology is only recommended if discharging of effluents through an existing mangrove forest can be achieved with a minimum investment on additional farm infrastructure.

Concluding Remarks

Honduran shrimp farming is characterized by relatively low stocking densities, which rarely exceed 10-15 PL/m^2 at harvest. This level of production, in conjunction with judicious feed and fertilizer management, has resulted in relatively low levels of nutrient discharges. Water exchange effluent and the initial 90% of pond drainage effluent from Honduran farms easily meet both initial and target GAA standards. Contrary to the general idea that high nutrient loadings result from the addition of feed to shrimp ponds, data indicates that unfertilized ponds in Honduras function as sinks of dissolved nutrients. Given the high natural fertility of estuarine waters, fertilization should be reduced to a minimum practical level or completely avoided. The situation is somewhat different for those farms in embayment locations, which may need to add fertilizer to promote natural productivity in the ponds.

Of the BMPs included in this analysis, the most effective appear to be those concerning careful water exchange and feed management. Honduran farmers must be commended for lowering water exchange rates to current levels, but additional efforts should be made to reduce water exchange frequency. Delaying water exchange to week 10 of the growout cycle would lead to considerable savings in pumping costs and drastic reductions in net discharges of TN, TP and BOD. Honduran farmers should attempt to perform water exchange only in response to some determined management criteria, such as DO levels.

Table 33. Annual enterprise budget for an 85-ha shrimp cooperative in Nicaragua based on 2001 prices and costs. Two production cycles per year were assumed.

Item	Description	Unit	Quantity	Price/ unit (US$)	Total cost (US$)
Gross Returns					
Shrimp	All sizes	lb	71,043	2.72	193,085
Variable Costs					
Post-larvae (PL)	Wild	1,000	11,900	2.50	29,750
Feed	25% protein	hundredweight	1,774	23.53	41,744
Fertilizer		hundredweight	-	9.80	-
Labor		dollars			19,148
Diesel		dollars			20,310
Equipment repairs		dollars			11,450
Pond preparation		ha	85	40.00	3,400
Lime		hundredweight	2,616	3.69	9,653
Filters	Two per pond	filter	12	40.61	487
Trips		dollars			4,600
Office stationary		dollars			180
Ice		hundredweight	1,093	2.60	2,842
Interest on operating capital	17% annual	dollars	145,814	0.06	8,263
Total variable costs (TVC)		dollars			151,827
Fixed Costs					
Debt payments					
Principal – this cycle		dollars			4,275
Interest – this cycle		dollars	4,275	0.06	242
Principal – previous cycle		dollars			20,117
Interest – previous cycle		dollars	20,117	0.17	3,420
Concession			90	25	2,250
Total fixed costs (TFC)					30,304
Total costs (TC)		dollars			182,131
Net returns		dollars			10,954
Net returns per unit area		dollars/ha			129
Breakeven price at 836 lb/ha		dollars/lb			2.56
Breakeven yield at US$2.72/lb		lb/ha/year			788

Research conducted on feed trays indicates that this simple technique may result in significant improvements to FCRs and concomitant reductions in nutrient loadings. Although it is not clear yet if these results can be reproduced on a commercial scale, application of the entire ration of feed in trays is recommended at a minimum on small farms. Feed trays may provide a mechanism for small farmers to compensate for the economies of scale on the unit cost of feed.

Treatment facilities such as settling basins appear to result in significant reductions in effluent concentrations of TP. Settling basins are relatively inexpensive in Honduras but they restrict the ability of farmers to engage in seasonal production in blocks.

Table 34. Effect of four BMPs on annual net returns/ha for the 26-ha artisanal shrimp farm in Honduras.

BMP	Net returns/ha in baseline scenario (US$/ha)	Net returns/ha in BMP scenario (US$/ha)	Change	Description of change
Reduction in water exchange rates from 10-11% to 5%	483	648	+34%	Total diesel cost decreased from US$7,701 to US$3,618.
Application of entire ration of feed on feed trays	483	751	+55%	Total feed cost decreased from US$24,753 to US$18,147.
Combined BMP: reduced water exchange rates and use of feed trays	483	916	+89%	Changes are described above.
Settling basin installation	483	244	-50%	Fixed costs increased by US$240/ha (annual amortized cost of basin)
Construction of mangrove biofilter – Natural forest	483	333	-31%	Fixed costs increased by US$150/ha (annual amortized cost of biofilter).
Construction of mangrove biofilter – Artificial forest	483	-442	-192%	Fixed costs increased by US$925/ha (annual amortized cost of biofilter).

Reductions in net returns were particularly great for the small farm scenario. A combination of improved feed management (via feed trays) and careful discharge of the last 10% of discharge effluent may represent a more feasible approach for small farms.

The integration of shrimp farms with mangrove wetlands is an innovative approach that should receive more research attention in the near future. Mangrove wetlands are known for their ability to absorb dissolved nutrients via denitrification or direct plant uptake; however, dissolved nutrients are already being removed by the cycling dynamics of Honduran shrimp ponds. Nonetheless, results from the Colombian experience and direct observations on some Honduran farms suggest that mangroves have also a great capability to remove particulate nutrients. Moreover, there are a number of advantages associated with the construction of mangrove wetlands that cannot be measured immediately in monetary terms; rather, benefits in various aspects will tend to accrue over the long term. Depending on existing local conditions, circulation of effluents through mangrove forests may be achieved with little investment in supporting farm infrastructure; in other cases biofilter construction may be more complicated, entailing extensive seeding of mangrove propagules and construction of roads and levees.

Table 35. Effect of four BMPs on annual net returns/ha for the 85-ha shrimp cooperative in Nicaragua.

BMP	Net returns/ha in baseline scenario (US$/ha)	Net returns/ha in BMP scenario (US$/ha)	Change	Description of change
Reduction in water exchange rates from 10-11% to 5%	129	255	+98%	Total diesel cost decreased from US$ 20,310 to US$ 10,155.
Application of entire ration of feed on feed trays	129	266	+106%	Total feed cost decreased from US$ 41,744 to US$ 30,987
Combined BMP: reduced water exchange rates and use of feed trays.	129	392	+204%	Changes are described above.
Settling basin installation	129	55	-57%	Fixed costs increased by US$ 74/ha (annual amortized cost of basin)
Construction of mangrove biofilter – Natural forest	129	43	-67%	Fixed costs increased by US$ 86/ha (annual amortized cost of biofilter).
Construction of mangrove biofilter – Artificial forest	129	-400	-410%	Fixed costs increased by US$ 529/ha (annual amortized cost of biofilter).

Because costs can rapidly escalate, sophisticated mangrove biofilters such as the one operating in Colombia cannot be recommended for small farms in Honduras. Financial incentives will likely be required to induce shrimp farmers to incur the expenses of a system with such characteristics.

Finally, the analysis of the small-scale shrimp farms in Honduras and Nicaragua revealed that, in addition to their positive impact on the environment, BMPs related to improved feed and water management are the key to improve production efficiency and increase current profit margins. In contrast, as these farms depend exclusively on borrowed capital to develop infrastructure and cover operating expenses, construction of treatment facilities (sedimentation basins and mangrove biofilters) would seriously hinder their financial viability.

Table 36. Estimates of total and net discharges of TN, TP, SRP and BOD_5 corresponding to two growout cycles in a 26-ha artisanal farm in Honduras under baseline conditions and four BMP scenarios. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation. Numbers in parenthesis indicate the percent change in discharge loading in the BMPs scenarios with respect to the baseline conditions.

BMP	Variable (kg/day/farm)							
	TN		TP		SRP		BOD_5	
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge
Baseline scenario	40.65	13.11	5.75	3.53	1.22	1.06	275	66
Reduction in water exchange rates from 10-11% to 5%	24.05 (-41%)	10.07 (-23%)	2.90 (-50%)	1.77 (-50%)	0.57 (-53%)	0.49 (-54%)	140 (-49%)	34 (-49%)
Application of entire ration of feed on feed trays	39.10 (-4%)	11.56 (-12%)	4.65 (-19%)	2.44 (-31%)	0.87 (-29%)	0.71 (-33%)	255 (-7%)	46 (-30%)
Combined BMP: reduced water exchange rates and use of feed trays	22.50 (-45%)	8.52 (-35%)	2.40 (-58%)	1.27 (-64%)	0.41 (-67%)	0.33 (-69%)	131 (-52%)	25 (-62%)
Settling basin installation	40.22 (-1%)	12.68 (-3%)	5.67 (-1%)	3.46 (-2%)	Undetermined		275 (0%)	66 (0%)

Table 37. Estimates of total and net discharges of TN, TP and BOD_5 corresponding to two growout cycles in an 85-ha shrimp cooperative in Nicaragua under baseline conditions and four BMP scenarios. Total nutrient discharge refers to the total quantity of nutrients released from ponds (including the initial load of intake water) while net discharge refers to the nutrient load attributable to shrimp pond operation. Numbers in parenthesis indicate the percent change in discharge loading in the BMPs scenarios with respect to the baseline conditions.

BMP	Variable (kg/day/farm)					
	TN		TP		BOD_5	
	Total discharge	Net discharge	Total discharge	Net discharge	Total discharge	Net discharge
Baseline scenario	120.90	36.82	20.80	2.44	1,625	117
Reduction in water exchange rates from 10-11% to 5%	75.66 (-37%)	28.55 (-22%)	12.09 (-42%)	1.80 (-26%)	917 (-44%)	73 (-38%)
Application of entire ration of feed on feed trays	117.45 (-3%)	33.37 (-9%)	20.31 (-2%)	1.95 (-20%)	1,591 (-2%)	83 (-29%)
Combined BMP: reduced water exchange rates and use of feed trays	72.20 (-40%)	25.10 (-32%)	11.84 (-43%)	1.56 (-36%)	900 (-45%)	55 (-53%)
Settling basin installation	119.27 (-1%)	35.19 (-4%)	20.34 (-2%)	1.97 (-19%)	1,625 (0%)	117 (0%)

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