Integrating Environmental Impacts, Productivity, and Profitability of Shrimp Aquaculture at the Farm-Scale as Means to Support Good Aquaculture Practices and Eco-Certification

Mitigating Negative Environmental Impacts/Study/09MNE03UM

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ABSTRACT

Nitrogen (N) and phosphorus (P) are key nutrients determining water quality in aquaculture. One component of this study employed mathematical modeling approach to examine the relationship among farm intensity, water management and nutrient dynamics over a complete production cycle. N dynamics included N input, assimilation, nitrification, and N loss through sedimentation, volatilization and discharge. P dynamics included P input, assimilation, and P loss through sedimentation and discharge. Models were calibrated for a commercial shrimp (*Litopenaeus vannamei*) farm in southern China. The models provided fairly good approximations to the observed values of total ammonia nitrogen (TAN), nitrate and nitrite (NO), chlorophyll (Chl) and total phosphorous (TP) ($R^2 = 0.94$). Model simulations indicated both stocking density and water exchange had significant impacts on concentrations of TAN, NO, TP and Chl. TAN, NO and TP levels increased with the intensification of the shrimp farming system. Chlorophyll concentration was mainly determined by water exchange. Nutrient loading was also increased with the intensification of the shrimp farming system. Approximately 701 kg N ha^{-1} $cycle^{-1}$ and 176 kg P ha^{-1} $cycle^{-1}$ were unutilized. Of them, 120 kg N ha^{-1} $cycle^{-1}$ in dissolved form (TAN+NO) and 62 kg P ha^{-1} $cycle^{-1}$ were discharged through regular daily water exchange. Moderate stocking density and reduced water exchange would be one solution to minimize environmental impacts of pond effluents and meanwhile maintain shrimp production. Future research should continue and concentrate on optimizing shrimp farming system to make the shrimp farming industry more sustainable.

Chinese shrimp farming is a diverse industry operated at different levels of intensity with different management strategies. The second component of this study aimed to capture farm diversity at regional level to evaluate system profitability for more sustainable development of shrimp farming. Risk of disease outbreak on farm economy and potential of implementing effluent treatment and participating certification programs were explored. Technical and economical characteristics of 100 farms in Hainan Province, China were surveyed during summer 2010 using an in-depth questionnaire. Multivariate analyses including factor and cluster analysis were employed to identify four farming systems by farm intensity, diversity, and labor origin. The categories were: intensive family and intensive commercial farms, semi-intensive and polyculture farms. Differences in management strategies affected farm profitability. Intensive family and commercial farms showed the highest profitability, followed by polyculture and semi-intensive farms. Influential factors to farm profitability were stocking density, aeration rate and feeding rate. Farm size and water exchange rate showed insignificant impacts on farm economy. Disease outbreak showed highest influence for intensive family and commercial farms, and least impacts for polyculture farms. In general, farm operators were not interested in establishing effluent treatment plans or participating in certification programs. Community members believed their quality of life was improved by shrimp farming in the region.

INTRODUCTION

Intensification of the shrimp farming industry has generated global concerns over its negative environmental impacts caused by unsustainable management (Casillas-Hernández et al., 2006; Naylor et al., 2000). Farm intensification uses more feed inputs, thus requiring more frequent flushing with new water and generating substantial amounts of waste materials such as nutrients, organic matter and suspended solids (Crab et al., 2007). Discharge of untreated pond effluents enriched in nutrients and organic matter may significantly contribute to high organic matter loads and thus cause eutrophication, hypoxia and turbidity in the receiving environment (Thomas et al., 2010). Effluent discharge also has potential of spreading disease pathogens and causing cross-farm pollution. Inefficient use of costly nutrients can also reduce farm profitability (Jackson et al., 2003). One of the major challenges facing sustainable development of shrimp farming is maintaining optimum water quality and minimizing nutrient loading. Good management practices are effective to reduce occurrence of water quality problems and achieve successful shrimp production. This urges on us the need to understanding nutrient dynamics and the implications of management in shrimp ponds.

Intensive shrimp farming in China is typically a flow-through system with high water exchange and aeration rates as means to maintain water quality at satisfactory levels for the crop. Most intensive farms operate in lined earthen ponds with average size of 0.2-0.4 ha. Farmers usually culture 2-3 crops per year in Southern China. According to our survey, intensive shrimp farming in southern China shows wide variation in management practices, with stocking densities from 75-180 post larvae (PL) m^{-2} and daily water exchange rates from 1-50% day^{-1}. Unit production ranges from 5-13 tonnes ha^{-1} $cycle^{-1}$, with feed conversion ratio (FCR) from 1.5-2.2.

Nitrogen (N) and phosphorous (P) components play important roles in water quality management. N is usually the key element limiting algal growth in marine aquaculture, while P is the critical nutrient in freshwater aquaculture (Goldman et al., 1974). Both of them can cause eutrophication problems when carrying capacity of a water body is exceeded. Previous studies on nutrient budgets in shrimp ponds indicated that the primary source of nutrients was feed, and the major sinks for nutrients were harvested shrimp, sediment and effluents (Casillas-Hernández et al., 2006; Funge-Smith and Briggs, 1998; Jackson et al., 2003; Xia et al., 2004). N and P inputs that are not incorporated into shrimp biomass are taken up by phytoplankton, settle as sediment, or are discharged with effluents. Different management practices can significantly affect water quality and thus shrimp growth in the pond. Modeling nutrient dynamics under different management scenarios is a fundamental step for understanding of feed utilization efficiency, changes in water quality and biogeochemical processes. Investigating the effects of farm intensity and water management on nutrient dynamics can help develop potential solutions to decrease nutrient loading and thus reduce environmental impacts of shrimp farms.

Mathematical modeling has been proven as a useful tool for a better understanding of nutrient dynamics in complex systems (Burford and Lorenzen, 2004; Jimenez-Montealegre et al., 2002). Optimization approaches are usually used to find parameters which best fit the model to observed data (Munoz-Tamayo et al., 2009). Several studies employed mathematical modeling to evaluate N dynamics in intensive shrimp ponds (Burford and Lorenzen, 2004; Lorenzen et al., 1997; Montoya et al., 1999). However, the dynamics of P flow in intensive shrimp ponds have not received much attention (Montoya et al., 2000).

Converted from traditional agriculture systems, Chinese shrimp farming is a diverse industry operated at different levels of intensity. The main cultured species in China is white-leg shrimp (*Litopenaeus vannamei*) due to its high economic value, low risk of disease, and short culture duration to reach market size. There are currently about 14,000 shrimp farms in China (Biao and Kaijin, 2007), usually classified by farm intensity and stocking density. This conceptual classification technique can often be misleading compared to other aquaculture systems such as tilapia farming. For example, semi-intensive tilapia farming relies only on natural food, while shrimp in semi-intensive farms feed on both natural food and commercial feed but are usually stocked at a much lower density than in intensive farms. Shrimp farming systems are generally more intensified than most of fish farming systems.

Identification of farm typology is an efficient method to summarize the diversity of production systems (Righi et al., 2011). Understanding the diversity of shrimp farming systems based on empirical classification and subsequently comparing their economic performance can facilitate decision-making for sustainable development. A multivariate technique, factor analysis, is usually employed to reduce the large number of initial variables to a limited number of significant factors. Such factors can then be elaborated by hierarchical or non-hierarchical clustering techniques to identify interesting farm groupings (Righi et al., 2011). Studies have employed these techniques to study characteristics of semi-intensive shrimp farming in Mexico (Ponce-Palafox et al., 2011), the typology of Asian carp (Michielsens et al., 2002), and Thai shrimp production systems (Joffre and Bosma, 2009). Agronomic and technical characteristics such as farming environment, farm size and level of intensification (Lazard et al., 2010) may be used to determine the typology of shrimp farming.

Economic analysis can provide a systematic evaluation of aquaculture activities, which in turn can lead to better management strategies towards economic sustainability. Economic sustainability of any farming system is examined by its profitability based on cost and profit analysis. Primary costs of shrimp farming include start-up investment and annual operating costs (Shang, 1981). Start-up investment costs include farm construction and equipment such as pumps and aerators. Annual operating costs can be further divided into fixed and variable costs. Fixed costs include land lease, depreciation, and maintenance of equipment. Variable costs include feed, seed, electricity, labor and other uses such as transportation. Farming systems with different management technologies may have significant differences in economic performance.

Risk of disease outbreak has a substantially negative influence on farm economy and has become a major concern in the shrimp industry. Disease outbreak can cause partial or massive crop failure, which can largely challenge sustaining production and affect profitability of the sector. Disease almost led to collapse of the shrimp industry in the 1990s in many Asian countries (Bhattacharya and Ninan, 2011). Over-intensification and many improper management practices such as discharge of untreated effluents into receiving waters make the current shrimp industry vulnerable to disease outbreak. Approximately 43 billion metric tons of untreated effluents from shrimp aquaculture discharge into the ambient aquatic environment each year in China (Biao and Kaijin, 2007). Discharge of untreated effluents may contaminate water quality and spread disease to adjacent farms. Few studies have evaluated the potential of adopting effluent treatment by shrimp farmers. Third-party certification is now viewed as a market-based tool for promoting better management practices and guaranteeing a price premium for maintaining good practice standards. Certification is an important factor affecting market price and thus farm profitability. Certification programs have not been widely established in China. The potential of shrimp farms in China to implement good management practices and participate in certification programs needs to be explored.

Quality of life is also considered as an important indicator of sustainability (Flores and Sarandón 2004). Many studies have discussed farmers' quality of life in sectors of aquaculture (Pomeroy et al. 2006), forestry (Kusel 2001) and livestock (Marker et al. 2005). Currently, few studies have yet applied a rigorous research of the role of shrimp aquaculture in tropical farmers' quality of life.

The objectives of the study were: 1) characterize N and P dynamics in intensive shrimp farming over a complete production cycle, 2) evaluate the diversity of shrimp farms towards its typology using multivariate techniques, 3) compare the identified farming systems for their technical characteristics and financial performance to determine the most profitable system, 4) assess key management practices that had significant impacts on farm profitability, 5) model risk of disease outbreak on farm economy, 6) investigate potential of implementing effluent treatment and participating certification programs by shrimp farmers, 7) evaluate change in quality of life caused by shrimp farming from perspectives of shrimp farmers and other villagers. Our results can provide practical insights for decision- or policy-making in order to promote good management practices towards economic sustainability.

METHODS

Data collection

During April-July 2010, field sampling for nutrient dynamic modeling was conducted in a commercial intensive shrimp farm in Hainan Province, China. Three lined earthen ponds (0.33 ha each) of the farm were selected and monitored as replicates over a complete production cycle. The ponds shared the same intensive culture practices. They were stocked with white shrimp *Litopenaeus vannamei* at 135 PL m^{-2}. Harvest occurred after about 100 rearing days. Shrimp were fed three times daily with local commercial feed which included 42% crude protein using feeding trays to determine actual consumption rates. Feeding rates were based on shrimp population density, with small adjustment daily to actual consumption in the feeding trays. Commercial pelleted feed was the only food applied and no fertilizer was added. Daily water exchange was implemented at rates of 1%, 5%, and 10% of the total pond water volume in the first, second and third month onwards, respectively. Effluents were continuously discharged into the receiving environment over the production cycle. Each pond was equipped with a paddlewheel at each pond corner and one in the pond center. Mechanical aeration was regularly used in each pond for a total (all paddle wheel time combined) of 20, 48 and 100 hours per day in the first, second and third month onwards, respectively. Thus water column was assumed to be well mixed so that a single sampling at any location was representative of the whole pond. A subsample of 50 shrimp was removed at biweekly intervals from each pond to assess shrimp growth throughout the culture period. Pond records were used to quantify total amounts of commercial feed added. At the end of the rearing cycle, shrimp were harvested by complete draining of the ponds and weighed to determine gross yield. Average production of the three ponds was 10.3 tonnes ha^{-1} $cycle^{-1}$ and FCR was approximately 1.7.

Water samples were collected weekly (sampling time at 1200-1300 h) at 20-30 cm below water surface from day 1 to harvest. Temperature, salinity, dissolved oxygen, pH, and turbidity were measured in the field using a portable water quality meter (Model WQC-24, Xebex International, Ltd.). Water samples were collected near the discharge gates and stored in clean plastic bottles, kept on ice, and transported to the laboratory for analysis immediately.

Total ammonia-N (TAN), nitrite-N (NO_2), nitrate-N (NO_3), total Kjeldahl nitrogen (TN), dissolved reactive phosphorous (DRP), total phosphorous (TP), Chlorophyll α (Chl) and total suspended solids (TSS) were analyzed. The determination of TAN, NO_2, NO_3, DRP, Chl and TSS were conducted according to standard methods (Strickland and Parsons, 1972; APHA, 1989). TN and TP was analyzed using a persulfate digestion method (Valderrama, 1981). Water quality data from the three ponds were treated as replicates, and mean values were used for model calibration. Shrimp carcass and shrimp feed were also analyzed for composition of N and P following standard methods (AOAC, 1980).

Data for socio-economic analysis was obtained during an in-depth survey in Hainan province, China from June to August 2010 with assistance of partners from Hainan University. The questionnaire for the survey was tested in the field and then improved in response to feedback before start of the general survey. The survey collected information on farm characteristics such as farm area, pond size, labor, feed use, farming techniques such as stocking density and aeration rate, production, costs, profits, disease outbreak, production problems, and farmers' attitudes on effluent treatment and certification. Based on farmers' conceptual classification, there were four main types of shrimp farming systems in Southern China. We randomly selected 25 shrimp farms from each type. A total of 100 shrimp farms differing in level of intensity, diversity, and labor origin were randomly sampled. For each survey site, farm owners or head managers were interviewed. Facility records were used for verification to reduce possible errors.

A range of economic indicators was selected and calculated using definitions following Shang (1981) and Joffre and Bosma (2009). Feed conversion ratio (FCR) represents the quantity of feed fed to grow one kg of aquaculture product. Labor productivity was calculated as total shrimp production in kg/ha per laborer day. Contracted labor hired on monthly or yearly basis was differentiated from occasional workers hired on a daily or weekly basis. Capital use efficiency was calculated as the net ratio of gross returns to capital costs (Michielsens et al., 2002). Capital cost included land, depreciation of equipment and operational costs (Michielsens et al., 2002).

Nutrient dynamic modeling

Conceptual models of N and P dynamics in intensive shrimp ponds were developed based on previous models (Lorenzen *et al.*, 1997; Burford and Lorenzen, 2004). Feed was considered as the only source of N and P input. Other sources such as inflow and precipitation were neglected due to their small contribution of less than 5% of the total (Lorenzen *et al.*, 1997).

Models were calibrated using our observed data. Following Lorenzen et al. (1997) and Burford and Lorenzen (2004), management parameters were derived directly from field data and fixed. VBGF growth parameters were estimated from shrimp weight at stocking and biweekly measurements. Mortality rate was estimated from numbers stocked and harvested and was assumed to be constant over time. N or P waste input rates were determined as mass balances by subtracting the N or P incorporated into shrimp tissue from the total feed N or P input. A few environment parameters such as extinction coefficients (k_{Chl} and k_{other}) were taken from the literature (Lorenzen *et al.*, 1997).

Nutrient dynamic parameters were estimated by first solving the ordinary differential equations and then fitting the model to observed time series data for TAN, NO, TP and Chl. Initial ranges for the estimated parameters were obtained from previous studies (Lorenzen *et al.*, 1997; Burford and Lorenzen, 2004). Calibration was carried out within the ranges via a maximum likelihood approach. The goodness of fit was evaluated using the principle of combined least sum of squared differences between observed and predicted values for TAN, NO, TP and Chl. The estimation process was a trial and error effort that sought a set of parameters which had the maximum likelihood and fitted the observed data most accurately. Using optimum estimated parameters, predictions of nutrient components (TAN, NO, TP and Chl) were generated by solving the models for a full production cycle. In order to evaluate model uncertainty, a sensitivity analysis was performed. Sensitivity analysis evaluated the changes in the model outputs with respect to variations of each estimated parameter, which were measured by sensitivity coefficients (Zi *et al.*, 2008).

Once calibrated, the models were used to simulate the impacts of variation in farm management (stocking density and water management) on pond water quality and effluents. End-of-cycle concentrations and loading of TAN, NO, TP, and Chl were generated for a range of stocking densities (75-180 PL m^{-2}) and water exchange rates (1-50% day^{-1}). The combined effects of stocking density and water exchange on nutrient levels and discharge were also evaluated.

Classification of farming types

A total of 14 technical variables were selected. They included: farm area (ha), total number of ponds, average pond size (ha), number of species cultured, shrimp stocking density (PL m^{-2}), number of crops per year, daily water exchange rate (% day^{-1}), aeration time (hours ha^{-1} $crop^{-1}$), feed use (kg ha^{-1} $year^{-1}$), start-up investment (RMB ha^{-1}), variable costs (RMB $year^{-1}$), fixed costs (RMB $year^{-1}$), ratio of family to total labor, and ratio of contracted to total labor.

Following Joffre and Bosma (2009), factor analysis was firstly employed to create a smaller set of composite variables. The new composite variables were orthogonal linear combinations of the original 14 variables. All variables were normalized and the factors were rotated using VARIMAX with Kaiser Normalization to increase interpretability (Michielsens et al., 2002). The extraction method used maximum likelihood. Factor scores were computed to replace the original 14 variables for further use in cluster analysis. Before applying factor analysis to the data set, Kaiser-Meyer-Olkin (KMO) and Bartlett's test were conducted to determine if the data fit model assumptions.

After factor analysis, shrimp farms were clustered according to the new factors. First, both hierarchical (Ward's method) and non-hierarchical (partitioning around medoids, PAM) cluster techniques were adopted to determine optimal number of clusters to ensure quality of results. PAM is a robust variation of well-known K-means method. Graphical results from the two methods were displayed to determine the optimal number of clusters. Then, results from PAM were used to obtain the cluster information. ANOVA and post hoc tests were used to determine if initial variables were significantly different in different clusters, with a significance level alpha at 0.05. Factor and cluster analyses were run using the libraries *stats* and *cluster* in R software environment (version 2.13.1).

Economic performance and influential factors

Economic performance of shrimp farms was compared by identified farming type to determine the most profitable farming system. Survival rate, shrimp yield, costs, profits, and key resource use efficiencies including capital, feed and labor were computed as indicators. ANOVA and post hoc tests were used to recognize significant differences of identified farming systems with a significance level alpha at 0.05.

Multiple regression analysis was used to predict yield (tons ha^{-1} yr^{-1}) and profits (RMB ha^{-1} yr^{-1}) as functions of management variables using the backward selection method. Management variables included farm size (ha), stocking density (PL m^{-2}), daily water exchange rate, aeration rate (hrs ha^{-1} yr^{-1}), feeding rate (tons ha^{-1} yr^{-1}). Independent variables were entered at probability ≤ 0.10.

Disease risk

Three disease scenarios including worst, best, and most probable case were modeled to help define the risk range for each farming system. Mortality rate due to disease outbreak in each case was used as the indicator. Farm owners or head managers were asked to provide or estimate mortality rate for each scenario based on farm records or disease outbreak history in the past five years. In this analysis, mortality rate represented the percent mortality of shrimp caused by disease outbreak in each farm. Shrimp yield was estimated based on the mortality rate for each scenario and compared with the base yield. The base yield was assumed as yield derived from the main survey.

Social analysis

For social analysis, another survey was conducted to investigate changes in quality of life of shrimp farmers and other farmers in the villages. Perceptions from 100 shrimp farmers and 100 other villagers were randomly collected. The questionnaire for the survey examined individual perceptions of health and wellbeing, community, crime and safety, education and work, and the environment. Data was analyzed using chi-square test with a significance level at 0.05.

RESULTS

Nutrient dynamic modeling

Most management and environment parameters were determined from field data and fixed (Table 1). Parameters to be estimated included s, n, v, g_{max}, I_{ratio}, k_{SN}, k_{SP}, c, u, b_P. The N and P dynamic models were optimized to extract a combination of 10 nutrient dynamics parameters that provided best fit to the observed data of TAN, NO, TP and Chl.

The calibrated models were run for the whole production cycle and simulated values were plotted against the observed values (Figure 1). The models provided fairly good approximations to the observed TAN, NO, TP and Chl concentrations with predicted values varying randomly from observed values (R^2=0.94). No significant differences were found between predicted and observed values of TAN, NO, TP and Chl ($P > 0.1$). TAN concentrations increased nearly exponentially and reached 1.9 mg l^{-1} by the end of production. Compared to TAN, NO increased mildly over the production cycle and reached maximum about 1 mg l^{-1} at the end. TP concentrations increased continuously during the first two months, declined slightly from day 60 to 70, and increased again subsequently. Chl concentrations increased gradually in the first month and reached an approximate plateau at 0. 32 mg l^{-1} during the final month of grow-out, but declined slightly at the end.
The combined effects of stocking density and water management on end-of-cycle concentrations of TAN, NO, TP, and Chl were simulated (Figure 2). Increasing stocking density and reduced water exchange rate increased the end-of-cycle concentrations of TAN, NO, and TP. NO and TP levels were dominated by water management when exchange rates were 20% day^{-1} or above. Chl concentrations were mainly determined by water exchange. Chl concentrations decreased with increasing water exchange, regardless of the stocking density. Lowest concentration of Chl was achieved at highest water exchange rate.
The combined effects of stocking density and water management on nutrient loading from one shrimp pond (pond size = 0.3 ha) were also simulated (Figure 3). At lower water exchange rate up to 20% per day, loading of NO was less than 10 kg from the pond (< 30 kg ha^{-1}). NO discharge reached maximum at the highest stocking density and 30% daily water exchange, and declined with higher water change rates. TAN discharge was less than 40 kg from the pond (< 120 kg ha^{-1}) with water exchange rate less than 20%, regardless of stocking density. With 20% of water exchange and above, loading of TAN increased with increasing stocking density and water exchange. Loading of TP showed a similar overall trend as that of TAN. Loading of Chl was mainly determined by water exchange, with an increasing trend for water exchange rates from 1-15% and then declining afterwards.

Classification and characterization

Data collected in this study were appropriate for a factor analysis, with KMO (Kaiser-Meyer-Olkin) of 0.838 (> 0.7 is relatively high) and Bartlett's test that was significant ($P < 0.05$). Factor analysis identified three orthogonal linear combinations of the 14 original, partially correlated variables. The three-factor solution cumulatively explained 86.1% of the total variance in the data, which was excellent (Table 2). Most uniqueness values were smaller than 0.5 and close to 0, which suggested the model fit well. We started by retaining and highlighting variables with loadings larger than 0.5 in absolute value to be the main components of each factor.

Factor 1 had nine main components, eight with positive signs (shrimp stocking density, number of crops, water exchange rate, aeration rate, feeding rate, start-up investment cost, variable and fixed costs) and one with a negative sign (average pond size). Factor 1 contrasted average pond size with the other main components. This factor therefore represented the intensification degree of shrimp farming, showing that intensive shrimp farms with positive scores on this factor usually operated smaller ponds with higher stocking density, more crops per year, higher water exchange and aeration rates, as well as higher level of start-up investment and operating inputs. Shrimp farms with positive scores on this factor represented intensive farms. Factor 1 accounted for 47.7% of the total variance.

Factor 2 was composed of two groups with four main components. The first group with positive signs included farm area, total number of ponds, and ratio of contracted to total labor. The second group with a negative sign consisted of ratio of family to total labor. Factor 2 indicated both farm scale and labor origin, and contrasted family based small- or medium-scale farms with commercial based large-scale farms. This factor accounted for 24.1% of the total variance in the set of 14 original variables.

Factor 3 had two main components and contrasted the number of species cultured with shrimp stocking density. It explained that stocking density was low in polyculture and high in monoculture farms. Factor 3 could be described as farm diversity. This factor explained 14.1% of total variance of the data.

Cluster analysis based on these three factors was used to identify principal farming types. Dendrogram, cluster, and silhouette plots reached an agreement showing the presence of four clusters (Figure 4, 5 and 6). The silhouette plot showed the silhouettes of all four clusters next to each other. The silhouette value summarized how appropriate each object's cluster was to the overall plot. The quality of clusters can be compared based on silhouette width (S_i, ranging from 0.25 to 0.5 indicate weak structure; 0.5-0.75 reasonable structure; and 0.75-1 strong structure). Silhouette width values of cluster 1, 3 and 4 were all larger than 0.75 which indicated a strong structure in each cluster. Cluster 2 had a relatively weak structure since the silhouette value was only 0.33. But the overall average silhouette width of the silhouette plot was 0.69 which indicated a reasonable overall structure was detected.

The four clusters represented four distinctively different types of shrimp farms. All farming types grouped by clustering analysis were characterized in terms of the 14 original technical variables in Table 3. Cluster 1 was intensive shrimp farms operated by families (intensive family); cluster 2 was intensive shrimp farms operated by commercial companies (intensive commercial); cluster 3 was semi-intensive shrimp farms, and cluster 4 polyculture farms.

Intensive family and commercial farms shared many similar characteristics. They both operated significantly smaller ponds with significantly higher stocking densities compared to semi-intensive and polyculture farms ($P < 0.05$). Both intensive farming systems produced shrimp year-round with a total of three crops and duration of 90-120 days per crop. They had significantly higher water exchange rates and aeration as well as higher feed use compared to the other two farming types ($P < 0.05$). The start-up investment and annual operating costs including fixed and variable costs were also significantly higher in the two intensive farming types than in semi-intensive and polyculture ($P < 0.05$). Intensive family had the highest start-up cost per hectare and annual fixed costs of all farming types ($P < 0.05$). In general, intensive family farms were relatively similar to intensive commercial farms in terms of intensification and farm diversity. They mainly differed in labor origin and farm size. Intensive family farms were small (< 3.3 ha) or medium (3.3-6.7 ha) scale with household members working in the farms. Intensive commercial farms had larger farm areas (> 6.7 ha) with only hired labor.

Semi-intensive and polyculture farms often operated ponds at least two-fold larger than those of intensive farming types. They were usually family based at small or medium scales. Semi-intensive farming used monoculture with lower stocking density and less intensification compared to intensive systems. Polyculture farms integrated shrimp culture with other fish, mainly tilapia. Polyculture farms had shrimp stocked at the lowest density, with only 38 post-larvae per m^2. Semi-intensive farms usually had two crops per year with duration of 120-150 days for each crop. Polyculture farms had two to three crops each year depending on the targeted harvest size of shrimp. Due to lower stocking density, water exchange and aeration rates were significantly lower for semi-intensive and polyculture farms than intensive farms ($P < 0.05$). Semi-intensive and polyculture farms used commercial feed and also relied on natural food produced in the pond. Thus they had significantly lower feed use per ha than intensive farming ($P < 0.05$). They also had lower start-up costs and annual operating costs than intensive farms.

Break down of operating costs by identified farming systems showed that feed was the major variable input cost in all farming systems (Table 4). Seed and electricity were the other high input costs in both intensive farming systems. Fertilizers and seed were also main input costs in the semi-intensive farming system. Of fixed costs, land lease was the major input cost in all farming systems.

Economic performance

Shrimp yields, production costs, profits, survival rates, and resource (feed, capital, and labor) use efficiency were computed for the four shrimp farming systems (Table 5). Semi-intensive farms had the highest shrimp survival rates at around 77%. Survival rates in the other farming systems were only 62%-65%. Intensive family and commercial farms had significantly higher shrimp yields than semi-intensive farms ($P < 0.05$) and the lowest shrimp yield was obtained in polyculture farms. Production costs per kilogram of shrimp were highest in intensive family and commercial farms (around US$ 2.7 based on current exchange rate), followed by semi-intensive (around US$ 2.1) and polyculture (around US$ 1.05) farms. Intensive family and commercial farms had similar profits, the highest of all systems (around US$ 9,500 ha^{-1} $crop^{-1}$), while semi-intensive farms obtained about half of that profit. By obtaining extra profit from other cultured species, polyculture farms obtained significantly higher profits than semi-intensive farms, but were still lower than intensive farms ($P < 0.05$).

Differences in resource use efficiency were also observed. The average feed conversion ratio (FCR) was similar for intensive family and commercial farms, which were significantly higher than semi-intensive and polyculture farms ($P < 0.05$). Semi-intensive and polyculture farms showed significantly higher capital use efficiency than intensive farms ($P < 0.05$). Labor productivity of intensive family and commercial farms was significantly higher than semi-intensive family farms. By integrating fish production, polyculture farms had the highest labor productivity. If fish production was excluded, labor productivity in polyculture farms would be the lowest.

Influential factors for yields and profits

Both models were similar with more than 90% of variability in the data explained by the same three predictor variables (Table 6 and 7). These predictor variables included stocking density, feeding rate and aeration rate, which had significant effects on yields and net profits and were considered influential factors. Two other independent variables, farm size and water exchange rate, showed insignificant impacts on the two response variables and thus were excluded from the models. All three influential factors were positively correlated with yields and net profits.

Disease risk

According to farm records and farmer's estimation, if disease occurred, an average of 78.4% of shrimp would die in the worst case, 35.6% in the most probable case, and 12.2% in the best case for all shrimp farms. Shrimp yields from the three scenarios including worst, best, and most probable case were estimated for each farming type and compared with base yields from disease free farms

(Figure 7). Disease outbreak showed highest influence on intensive farming, especially on intensive family farms. Polyculture farms were least affected by disease occurrence.

Perceptions of changes in quality of life

All respondents agreed that shrimp farming had significant positive impacts on the development of their community in general during the last 10 years ($P < 0.05$). The positive impacts included: 1) higher standard of living, including more job opportunity and higher salary; 2) the environment of the village was generally better than in the past, for example, more roads were built; 3) more educational opportunity for children; 4) less crime in the village; 5) less illness than in the past, and people who got sick had more access to medical service; and 6) villages had grown in the last 10 years. However, farmers also agreed that more water and soil pollution were caused by shrimp farming in the region.

DISCUSSION

The dynamic models developed provided satisfactory fits ($R^2 = 0.94$) to the time series concentrations of TAN, NO, TP and Chl for the Chinese commercial shrimp farm. Most estimated parameters were comparable with the ranges provided by a pioneer study (Lorenzen et al., 1997). Predicted concentrations of nutrient components were also consistent with corresponding values in previous studies on shrimp farming (Lorenzen et al., 1997; Funge-Smith and Briggs, 1998; Jackson et al., 2003; Burford and Lorenzen, 2004). There were several comprehensive models on N and P dynamics in aquacultural systems (Lorenzen et al., 1997; Montoya et al., 2000; Jimenez-Montealegre et al., 2002; Burford and Lorenzen, 2004). Those studies were focused on systems under different environmental conditions and management scenarios, and therefore could not be directly compared to our results. This study could serve as a basis for integrating management parameters such as farm intensity and water exchange to simulate nutrient discharge by fish ponds in relation to time. Results of the models could be utilized for examining potential environmental impacts of shrimp farming and advising the regulation for more sustainable development of the sector.

Several studies on nutrient mass balances in shrimp ponds indicated that the major source of nutrient input was shrimp feed (Funge-Smith and Briggs, 1998; Jackson et al., 2003; Casillas-Hernández et al., 2006). N and P loads to the environment depended to the quantity and quality of feed input (Castello et al., 2008). In general, about 75% of the feed N and P were unutilized and entered the water column as waste (Crab et al., 2007). In this study, only 32% of N and 15% of P inputs from feed were incorporated into shrimp biomass. The estimated environmental losses of N and P per ton of shrimp produced for the model shrimp system were 72 and 18 kg/ton, respectively. Nutrient losses were about 701 kg N ha^{-1} $cycle^{-1}$ and 176 kg P ha^{-1} $cycle^{-1}$ from Chinese intensive shrimp ponds. Of these losses, 120 kg N ha^{-1} $cycle^{-1}$ in dissolved form (TAN+NO) and 62 kg P ha^{-1} $cycle^{-1}$ were discharged through regular daily water exchange. Other major sinks of N and P would be sediment and harvest drainage. Our results were comparable with previous studies, which indicated about 18%-22% of the input N and 6%-14% of input P were assimilated by shrimp (Funge-Smith and Briggs, 1998; Jackson et al., 2003; Xia et al., 2004). Estimated nutrient losses from intensive shrimp ponds were about 860 kg N ha^{-1} $cycle^{-1}$ and 184 kg P ha^{-1} $cycle^{-1}$ (Briggs and Funge-Smith, 1994). The estimated environmental losses of N and P per ton of shrimp produced in semi-intensive shrimp ponds were 73.3 and 13.2 kg/ton, respectively (Casillas-Hernández et al., 2006). Our results of nutrient losses per ton of shrimp produced were comparable with those of semi-intensive systems due to high unit production in the intensive ponds.

The relationship of stocking density, water management and nutrient concentrations is complex and poorly understood (Lorenzen et al., 1997). Water exchange and stocking density can influence most water quality parameters, including ammonia, nitrite, nitrate, Kjeldahl nitrogen, soluble orthophosphate and phytoplankton (Hopkins et al., 1993). Our simulation results consistently showed that both stocking density and water exchange had important effects on TAN, NO and TP levels. At high stocking densities, high rates of water exchange were required to substantially reduce nutrient levels in ponds. Since the maximum phytoplankton assimilation capacity was already achieved, concentration of Chl was mainly affected by water exchange. Both stocking density and water exchange could influence nutrient loading. According to our results, low stocking density and reduced water exchange could decrease nutrient loading to receiving waters.

System optimization through better management is essential for future shrimp farming to be more sustainable. System optimization requires minimizing nutrient loading and maximizing shrimp production. This puts us in a dilemma. Minimizing nutrient loading needs us to reduce water exchange and use lower stocking density. But increasing stocking density is a key approach to maximize shrimp production, and increasing water exchange is needed to achieve a higher survival rate for ponds with high stocking density. To solve the dilemma, voluntary adoptions of best management practices (BMPs) or good aquaculture practices (GAPs) have been promoted recently as a reasonable and affordable means to maintain relatively high production and meanwhile minimize environmental impacts from pond effluents (Stanley, 2000; Boyd, 2003). Nutrient loads in pond effluents may be minimized through applications of some BMPs and GAPs including moderate stocking density within the assimilation capacity of ponds and reduced water exchange rate (Boyd, 2003). Lower stocking density reduces total N and P inputs and lower water exchange rate reduces effluent quantities. The estimated environmental losses of N and P per ton of shrimp produced for the model shrimp system were 72 and 18 kg/ton, respectively. Other BMPs and GAPs such as sludge removal, optimum feeding regimes and sufficient mechanical aeration are also critical in controlling nutrient dynamics in the pond and reducing loading to the receiving waters.

Shrimp farming in China is highly diversified and concentrated, but geographically divided. Most production occurs in southern China, mainly Guangdong, Fujian, Hainan, and Zhejiang provinces. Shrimp farms anually culture two to three crops per year in southern China, while only one to two crops in northern China (Biao and Kaijin, 2007). The majority of extensive shrimp farms have been replaced by more intensified farming types. For our analysis, a total of 100 shrimp farms across the concentrated shrimp farming region in Hainan province were included. Total area of our sampled farms was 715 hectares, representing 8.5% of shrimp farming area in this province in 2010. Joffre and Bosma (2009) failed to include larger intensive commercial farms due to limited access to these farms because of contamination and disease issues. Under the assistance of local technicians, we were able to visit a few large commercial farms wearing special uniforms after strict sterilization procedures, and successfully incorporated them into our study.

Aquaculture typologies are often determined by levels of farm intensity, using indicators such as stocking density and level of inputs (Joffre and Bosma, 2009). Following Joffre and Bosma (2009), we employed similar variables that reflected operating characteristics, diversity, and labor origin of shrimp farms. We also added new technical variables such as water exchange rate and aeration rate. Rather than using a traditional conceptual classification by intensity in uni-dimensional manner (usually just stocking density), we employed multivariate analysis to develop an empirical-based multi-dimensional typology, which better captured the true complexity of shrimp farming sector (Michielsens et al., 2002). The analysis helped us identify four types of shrimp farming systems distinguished by intensity, origin of labor and species diversity: intensive family and commercial, semi-intensive and polyculture of shrimp with tilapia. Our classification results were consistent with information of farm type provided by shrimp farmers.

Farm profitability is always influenced by management practices and fluctuation of market price (Paul and Vogl, 2011). Poor management can lead to reduced production and lower profitability even when prices rise (Smith et al., 2010). Though operated at highest costs with highest feed use, the two intensive farming systems were still the most profitable types and performed well in terms of capital and labor use. This was due to high shrimp yields and better market prices. Intensive farms tended to grow larger shrimp by using specific pathogen free (SPF) post-larvae, and sold them at a higher farm-gate price. Joffre and Bosma (2009) stated that intensive farming systems were generally economically sustainable in a short term but not on the long term. Future research is needed to improve intensive systems to achieve long-term economic sustainability. Our study found survival rates were higher in semi-intensive ponds than intensive ponds due to lower stocking density and better water quality in the former ponds. High survival rates of shrimp could also be achieved in small intensive ponds under better management practices (Ruiz-Velazco et al., 2010).

Polyculture outperformed semi-intensive and ranked as the third most profitable farming system. Most polyculture farms were actually converted from semi-intensive farms to gain extra profits that would compensate for risk of disease outbreak. By integrating shrimp farming with fish and maintaining shrimp at a lower density, polyculture farms had more secure production and their financial risk was reduced. However, polyculture did not prevent farms from virus infections and farms were still vulnerable to disease if inappropriately managed. In our study, polyculture farms integrated shrimp and tilapia with ratios of 10:1 (30 PL per m^2 and 3 fish per m^2 for fish with size of 10 g) or 15:1 (45 PL per m^2 and 3 fish per m^2 for fish with size of 10 g) in earthern ponds. Those ratios were considered as optimum and recommended by local researchers.

Stocking density, feeding and aeration rate were the key management techniques which could significantly influence farm profitability in Chinese shrimp farming systems. Though stocking density was positively correlated to profitability, it should not exceed a pond's carrying capacity. Schwantes et al. (2009) found feeding rate and water exchange had the greatest impacts on prawn production in Thailand. They also included indirect predictors that were descriptive of the management strategy such as stocking PLs directly or nursing them in separate ponds, and found a farmer's years of experience and harvest methods also had significant impacts on net profits. We found farm size and water exchange rate had insignificant effects on farm profits. Pond size was also shown to be important in explaining profitability of shrimp farms by Gordon and Bjørndal (2009). Small production units may also lead to better management (Milstein et al., 2005). Ruiz-Velazco et al. (2010) also found that aeration was an important factor determining survival rates and final production for shrimp ponds in intensive commercial farms. High aeration rates or earlier start of aeration resulted in higher survival rates. In that study, raising aeration from 9000 to 14000 horsepower per hour per hectare increased production by 32%. Starting aeration after 5 weeks resulted in an 18% decrease in shrimp yield compared to starting at the beginning of the culture cycle (Ruiz-Velazco et al., 2010).

Shrimp farmers were also asked to rank the major problems that might significantly affect farm profitability during our survey. The top five problems were: disease outbreak, low farm-gate price, poor seed quality, high feed price and poor water quality. Disease outbreak was identified as the most important problem and was attributed to external pollution, poor water and seed quality by farmers. Thai prawn farmers also cited external pollution, seed qualty, pond water quality and poor soil quality as the main causes of disease prevalence (Schwantes et al., 2009). External pollution was mainly caused by agricultural and aquacultural activities. Specific pathogen free (SPF) strains of white shrimp were introduced from North America to solve the issue of poor seed quality, as they were more disease resistant and grew faster than local strains. A shift from black shrimp to SPF white shrimp enabled Thailand to reduce the risk of disease outbreak in the shrimp industry (Bhattacharya and Ninan, 2011). However, new diseases emerged and disease problems still disturbed this sector (Bhattacharya and Ninan, 2011). Our results indicated that disease outbreak could cause only 12% to 36% crop failure in the best or most probable cases, and as much as 78% crop failure in the worst cases. Disease risk usually depends on the causes of disease, such as bacteria or virus based, time of disease occurrence, shrimp size at that time, and management stategies. Most shrimp farmers harvest once disease is detected while shrimp are still marketable. The risk of disease also rose with increased intensity and stocking densities, and when polyculture was replaced by monoculture (Kautsky et al., 2000). Approximately 26% of farms in our survey reported experiencing partial crop failure caused by disease outbreak in the past. Most of these were intensive family-based farms. Disease outbreak had larger impacts on intensive farming, particularly intensive family farms, than on semi-intensive and polyculture. This was probably because high stocking density facilitated the spread of pathogens. Under the worst case scenario in our model, massive crop failure would produce zero to negative returns for both types of intensive farms, while most polyculture farms could still gain positive profits. Joffre and Bosma (2009) found that intensive commercial farms had significantly lower percentages of disease outbreak compared to intensive family and polyculture farms in Vietnam. They indicated that higher technological investments in water treatment and water quality monitoring could reduce the risk of disease outbreak. However, they were unable to survey many larger intensive commercial farms in their study. They also recommended minimizing water exchange to prevent contamination by external pollution. Aeration management in intensive ponds was also recommended as an approach to reduce mortality from disease (Ruiz-Velazco et al., 2010).

The majority of farms (86%) in our survey discharged untreated effluents directly into receiving waters. Only a few intensive commercial farms treated pond effluents using chemical or biological techniques before discharge. However, all interviewed farmers were aware of the potential problems caused by discharge of untreated pond effluents. More than half of farms (58%) in our survey were reluctant to invest money on effluent treatment and would only be willing to implement effluent treatment under mandatory requirement by the government.

Given the high tradability of shrimp, trade policy can be another mechanism to promote more sustainable production. Leading shrimp importers, including the United States, Japan, and the European Union, have imposed more stringent trade policies to ensure quality of imported shrimp. There is a growing demand for eco-labeled or certified shrimp products from these developed countries. Third-party certification and eco-labeling are private initiatives which can differentiate shrimp products from well managed or poorly managed farms (Smith et al., 2010). Leading importers are willing to pay a premium for shrimp with eco-labels or shrimp produced by certified farms that adopt good aquaculture practices (GAP) or best management practices (BMP). One of the main problems with establishing certification guidelines around the world is due to lack of comprehensive information about the local environmental impacts of aquaculture (WWF, 2008). GAP and BMP standards for shrimp farm certification were initially designed for large-scale commercial farms (Boyd, 2011). Certification programs have not been widely established in China since the majority of shrimp farms are small-scale, family operated. Even for commercial large-scale farms, only a few are certified. Certification programs are currently evaluating ways to integrate and group small-scale farms for inspection and certification by the use of farm clusters or cooperatives (Boyd, 2011). Many respondants in our survey (42%), mostly from intensive farms, showed interest in participating in certification programs for a better market price of shrimp. The rest (58%) expressed no interest at all and thought it was waste of money to be certified. An interesting shift of commodity chain from simple buyer-driven to twin-driven mode has been observed in Bangladesh. In the twin-driven commodity chain, buyers govern the supply network and third-party certifiers control the regulatory aspects of the industry (Islam, 2008). This new commodity chain offers great opportunities for sustainable shrimp farming by adopting GAP or BMP and participating in certification programs. It could be a model for the Chinese shrimp farming industry to promote more sustainable production.

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LITERATURE CITED

AOAC, 1980. Official methods of analysis of the Association of Official Analytical Chemists (13th edition, edited by W. Horwitz). Association of Official Analytical Chemists, Washington, DC.

APHA, 1989. Standard methods for the examination of water and wastewater, 17th ed. . American Public Health Association, American Water Works Association, Water Pollution Control Federation, Washington, DC.

Bhattacharya, P., K.N. Ninan, 2011. Social cost-benefit analysis of intensive versus traditional shrimp farming: A case study from India. Natural Resources Forum, 2011:1-13.

Biao, X., and Y. Kaijin, 2007. Shrimp farming in China: Operating characteristics, environmental impact and perspectives. Ocean and Coastal Management, 50:538-550.

Boyd, C.E., 2003. Guidelines for aquaculture effluent management at the farm-level. Aquaculture 226, 101-112.

Boyd, C.E., 2011. Applying effluent standard to small-scale farms. www.aquaculturecertification.org Accessed on August 2, 2011.

Burford, M.A., Lorenzen, K., 2004. Modeling nitrogen dynamics in intensive shrimp ponds: the role of sediment remineralization. Aquaculture 229, 129-145.

Cao, L., J.S. Diana, G.A.Keoleian, and Q. Lai, 2011. Life cycle assessment of chinese shrimp farming systems targeted for export and domestic sales. Environmental Science and Technology, 45: 6531-6538.

Casillas-Hernández, R., Magallón-Barajas, F., Portillo-Clarck, G., Páez-Osuna, F., 2006. Nutrient mass balances in semi-intensive shrimp ponds from Sonora, Mexico using two feeding strategies: Trays and mechanical dispersal. Aquaculture 258, 289-298.

Crab, R., Avnimelech, Y., Defoirdt, T., Bossier, P., Verstraete, W., 2007. Nitrogen removal techniques in aquaculture for a sustainable production. Aquaculture 270, 1-14.

Flores, C.C., and S.J.Sarandón, 2004. Limitations of neoclassical economics for evaluating sustainability of agricultural systems: comparing organic and conventional systems. Journal of Sustainable Agriculture, 24(2):77-91.

Funge-Smith, S.J., Briggs, M.R.P., 1998. Nutrient budgets in intensive shrimp ponds: Implications for sustainability. Aquaculture 164, 117-133.

Goldman, J.C., Tenore, K.R., Ryther, J.H., Corwin, N., 1974. Inorganic nitrogen removal in a combined tertiary treatment—marine aquaculture system—I. Removal efficiences. Water Research 8, 45-54.

Gordon, D.V., and T. Bjørndal, 2009. A comparative study of production factors and productivity for shrimp farms in three Asian countries: Bangladesh, India, and Indonesia. Aquaculture Economics and Management ,13:176-190.

Hopkins, J.S., Hamilton Ii, R.D., Sandifer, P.A., Browdy, C.L., Stokes, A.D., 1993. Effect of water exchange rate on production, water quality, effluent characteristics and nitrogen budgets of intensive shrimp ponds. Journal - World Aquaculture Society 24, 304-320.

Islam, M.S., 2008. From pond to plate: Towards a twin-driven commodity chain in Bangladesh shrimp aquaculture. Food Policy, 33:209-223.

Jackson, C., Preston, N., Thompson, P.J., Burford, M., 2003. Nitrogen budget and effluent nitrogen components at an intensive shrimp farm. Aquaculture 218, 397-411.

Jimenez-Montealegre, R., Verdegem, M.C.J., Van Dam, A., Verreth, J.A.J., 2002. Conceptualization and validation of a dynamic model for the simulation of nitrogen transformations and fluxes in fish ponds. Ecological Modelling 147, 123-152.

Joffre, O.M., and R.H. Bosma, 2009. Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. Agriculture, Ecosystems and Environment, 132:153-159.

Kautsky, N., P. Rönnbäck, M. Tedengren, and M. Troell, 2000. Ecosystem perspectives on management of disease in shrimp pond farming. Aquaculture, 191:145-161.

Kusel, J., 2001. Assessing well-being in forest dependent communities. Journal of Sustainable Forestry, 13:359-384.

Lazard, J., A. Baruthio, S. Mathé, H. Rey-Valette, E. Chia, O. Clément, J. Aubin, P. Morissens, O. Mikolasek, M. Legendre, P. Levang, J.P. Blancheton, and F. René, 2010. Aquaculture system diversity and sustainable development: Fish farms and their representation. Aquatic Living Resources, 23:187-198.

Lorenzen, K., Struve, J., Cowan, V., 1997. Impact of farming intensity and water management on nitrogen dynamics in intensive pond culture: a mathematical model applied to Thai commercial shrimp farms. Aquaculture Research 28, 493-507.

Marker, L.L., Dickman, A.J., McDonald, D.W., 2005. Perceived effectiveness of livestock-guarding dogs placed on Namibian farms. Rangeland Ecology and Management 58 (4), 329-336.

Michielsens, C.G.J., K. Lorenzen, M.J. Phillips, and R. Gauthier, 2002. Asian carp farming systems: Towards a typology and increased resource use efficiency. Aquaculture Research, 33:403-413.

Milstein, A., M.S. Islam, M.A. Wahab, A.H.M. Kamal, and S. Dewan, 2005. Characterization of water quality in shrimp ponds of different sizes and with different management regimes using multivariate statistical analysis. Aquaculture International, 13:501-518.

Montoya, R.A., Lawrence, A.L., Grant, W.E., Velasco, M., 2000. Simulation of phosphorus dynamics in an intensive shrimp culture system: effects of feed formulations and feeding strategies. Ecological Modelling 129, 131-142.

Montoya, R.A., Lawrence, A.L., Grant, W.E., Velaso, M., 1999. Simulation of nitrogen dynamics and shrimp growth in an intensive shrimp culture system: effects of feed and feeding parameters. Ecological Modelling 122, 81-95.

Munoz-Tamayo, R., Laroche, B., Leclerc, M., Walter, E., 2009. IDEAS: A Parameter Identification Toolbox with Symbolic Analysis of Uncertainty and Its Application to Biological Modelling. pp. 1271-1276.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017-1024.

Paul, B.G., and C.R. Vogl, 2011. Impacts of shrimp farming in Bangladesh: Challenges and alternatives. Ocean and Coastal Management, 54:201-211.

Pomeroy, R.S., Parks, J.E., Balboa, C.M., 2006. Farming the reef: is aquaculture a solution for reducing fishing pressure on coral reefs? Marine Policy 30 (2), 111-130.

Ponce-Palafox, J.T., A. Ruiz-Luna, S. Castillo-Vargasmachuca, M. García-Ulloa, and J.L.

Arredondo-Figueroa, 2011. Technical, economics and environmental analysis of semi-intensive shrimp (Litopenaeus vannamei) farming in Sonora, Sinaloa and Nayarit states, at the east coast of the Gulf of California, México. Ocean and Coastal Management, 54:507-513.
Righi, E., S. Dogliotti, F.M. Stefanini, G.C. Pacini, 2011. Capturing farm diversity at regional level to up-scale farm level impact assessment of sustainable development options. Agriculture, Ecosystems and Environment, 142:63-74.
Ruiz-Velazco, J.M.J., A. Hernández-Llamas, V.M. Gomez-Muñoz, and F.J. Magallon, 2010. Dynamics of intensive production of shrimp Litopenaeus vannamei affected by white spot disease. Aquaculture, 300:113-119.
Schwantes, V.S., J.S. Diana, and Y. Yi, 2009. Social, economic, and production characteristics of giant river prawn Macrobrachium rosenbergii culture in Thailand. Aquaculture, 287:120-127.
Shang, Y.C., 1981. Aquaculture economics: basic concepts and methods of analysis. Croom Helm, London, UK.
Smith, M.D., C.A. Roheim, L.B. Crowder, B.S. Halpern, et al., 2010. Sustainability and global seafood. Science, 327:784-786.
Stanley, D.L., 2000. The economics of the adoption of BMPs: the case of mariculture water management. Ecological Economics 35, 145-155.
Strickland, J.D.H., Parsons, T.R., 1972. A Practical Handbook for Seawater Analysis, second ed. Fisheries Research Board of Canada, p. 310.
Thomas, Y., Courties, C., El Helwe, Y., Herbland, A., Lemonnier, H., 2010. Spatial and temporal extension of eutrophication associated with shrimp farm wastewater discharges in the New Caledonia lagoon. Marine Pollution Bulletin 61, 387-398.
Valderrama, J.C., 1981. The simultaneous analysis of total nitrogen and total phosphorus in natural waters. Marine Chemistry, 109-122.
WWF, 2008. Aquaculture Dialogues Process Guidance Document. www.worldwildlife.org.
Xia, L.Z., Yang, L.Z., Yang, M.C., 2004. Nitrogen and phosphorus cycling in shrimp ponds and the measures for sustainable management. Environmental Geochemistry and Health 26, 245-251.
Zi, Z., Zheng, Y., Rundell, A., Klipp, E., 2008. SBML-SAT: a systems biology markup language (SBML) based sensitivity analysis tool. BMC bioinformatics 9, 342.

Table 1. Model parameters.

Model parameters	Values	Reference
Management/environment parameters (fixed)		
K (shrimp VGBF growth rate, % day^{-1})	0.84	
W_{∞} (shrimp VGBF maximum weight, g)	72	
W_0 (shrimp VGBF stocking weight, g)	0.08	
N_0 (stocking density, PL l^{-1})	0.09	
M (mortality rate, % day^{-1})	0.5	
z (water depth, m)	1.5	
a_N (N input rate, mg N g^{-1} shrimp day^{-1})	1.1	
a_P (P input rate, mg P g^{-1} shrimp day^{-1})	0.25	
q (proportion of N entering as TAN)	0.9	Burford and Lorenzen, 2004
b_N (allometric scaling of TAN input)	0.75	Lorenzen et al. (1997)
k_{other} (extinction coefficient non-Chl)	4	Lorenzen et al. (1997)
k_{chl} (extinction coefficient Chl)	11.9	Lorenzen et al. (1997)
f (water exchange rate, % day^{-1})		
Month 1	1	
Month 2	5	
Month 3 onwards	10	
Nutrient dynamics parameters (estimated)		
s (sinking rate of dead algae, % day^{-1})	6.4	
n (nitrification rate, % day^{-1})	9.9	
v (volatilization rate, % day^{-1})	4.8	
g_{max} (maximum algae daily growth rate, day^{-1})	0.59	
I_{ratio} (ratio surface/saturation light intensity)	0.83	
k_{SN} (N half-saturation, mg l^{-1})	0.0043	
k_{SP} (P half-saturation, mg l^{-1})	0.0036	
c (nitrogen-to-chl ratio)	4.8	
u (phosphorus-to-Chl ratio)	2.1	
b_P (allometric scaling of TP input)	0.69	

Table 2. The rotated factor matrix, result from a maximum likelihood analysis based on 14 variables from 100 shrimp farms.

Parameters	Factor			Uniqueness
	1	2	3	
Farm area (ha)	.098	.966	.219	0.01
Total number of ponds	.226	.916	.288	0.028
Average pond size (ha)	-.761	-.199	-.193	0.344
Number of species cultured	-.351	.068	-.929	0.009
Shrimp stocking density (PL m^{-2}) *	.709	.114	.646	0.068
Number of crops	.857	.281	.175	0.156
Water exchange rate (%)	.729	.237	.403	0.25
Aeration rate (hours ha^{-1} $year^{-1}$)	.873	.306	.269	0.071
Feeding rate (tons ha^{-1} yr^{-1})	.887	.406	-.195	0.011
Start-up investment cost (RMB ha^{-1}) #	.908	.176	.305	0.05
Variable costs (RMB $year^{-1}$)	.919	.369	.127	0
Fixed costs (RMB $year^{-1}$)	.905	-.037	.197	0.15
Ratio family/total labor	-.252	-.694	.151	0.432
Ratio contracted/total labor	.229	.721	-.226	0.377
% of the total variation explained by the factor	47.7	24.3	14.1	

Note: *PL= post larvae; #1 RMB = 0.15 USD.

Table 3. Technical characteristics of Chinese shrimp farming systems identified by cluster analysis.

	Cluster			
	Intensive family	**Intensive commercial**	**Semi-intensive**	**Polyculture**
Numbers	25	25	25	25
Farm area (ha)	3.14 ± 1.72^{b}	17.8 ± 8.35^{a}	2.84 ± 1.5^{b}	4.9 ± 3.35^{b}
Total number of ponds	9 ± 6^{b}	51 ± 24^{a}	3 ± 2^{b}	6 ± 4^{b}
Average pond size (ha)	0.309 ± 0.05^{b}	0.311 ± 0.04^{b}	0.759 ± 0.23^{a}	0.725 ± 0.22^{a}
Number of species cultured	1 ± 0.0^{b}	1 ± 0.0^{b}	1 ± 0.0^{b}	2 ± 0.0^{a}
Shrimp stocking density (PL m^{-2})	144 ± 19^{a}	140 ± 14^{a}	92 ± 9^{b}	38 ± 8^{c}
Number of crops	3 ± 0.0^{a}	3 ± 0.0^{a}	2 ± 0.0^{c}	2.16 ± 0.374^{b}
Water exchange rate (% day^{-1})	17.2 ± 5.79^{a}	17 ± 4.79^{a}	6.44 ± 2.45^{b}	3.12 ± 1.27^{c}
Aeration rate (hrs ha^{-1} $year^{-1}$)	$54{,}700 \pm 108{,}00^{a}$	$60{,}000 \pm 9{,}640^{a}$	$6{,}190 \pm 1{,}670^{b}$	$7{,}920 \pm 2{,}200^{b}$
Feeding rate (ton ha^{-1} $year^{-1}$)	50.9 ± 4.7^{a}	50.6 ± 5.29^{a}	14.1 ± 1.83^{c}	34.8 ± 4.34^{b}
Start-up costs (RMB ha^{-1})	$528{,}000 \pm 31{,}400^{a}$	$476{,}000 \pm 13{,}200^{b}$	$174{,}000 \pm 22{,}200^{c}$	$163{,}000 \pm 13{,}700^{c}$
Variable costs (RMB ha^{-1} $year^{-1}$)	$552{,}000 \pm 45{,}500^{a}$	$567{,}000 \pm 51{,}600^{a}$	$158{,}000 \pm 14{,}500^{c}$	$24{,}9000 \pm 27{,}000^{b}$
Fixed costs (RMB ha^{-1} $year^{-1}$)	$96{,}800 \pm 15{,}800^{a}$	$70{,}200 \pm 8{,}790^{b}$	$32{,}100 \pm 4{,}880^{c}$	$33{,}300 \pm 4{,}670^{c}$
Ratio family/total labor	0.42 ± 0.2^{b}	0^{d}	0.6 ± 0.27^{a}	0.27 ± 0.19^{c}
Ratio contracted/total labor	0.49 ± 0.2^{c}	0.89 ± 0.1^{a}	0.31 ± 0.25^{d}	0.68 ± 0.17^{b}

Note: cluster values were presented as mean ± standard deviation. Values in the same row with different superscript letter were significantly different ($P < 0.05$).

Table 4. Break down of operating costs by farming system.

	Intensive family	Intensive commercial	Semi-intensive	Polyculture
Feed	61%	63%	51%	74%
Fertilizers	0%	0%	9%	1%
Seed	10%	8%	8%	3%
Chemicals	4%	6%	4%	1%
Electricity	8%	8%	7%	4%
Labor	2%	3%	3%	4%
Other	1%	1%	2%	1%
Total variable costs	**86%**	**89%**	**83%**	**88%**
Land lease	8%	6%	9%	7%
Depreciation	6%	3%	6%	4%
Maintenance	0%	1%	1%	1%
Total fixed costs	**14%**	**11%**	**17%**	**12%**

Table 5. Comparison of economic performance and resource use efficiency of shrimp farming systems (mean ± S.D.).

Parameters	**Cluster**			
	Intensive family	**Intensive commercial**	**Semi-intensive**	**Polyculture**
Survival rate (%)	62.6 ± 8.2^{b}	62.4 ± 7.5^{b}	77.2 ± 3.8^{a}	65.6 ± 7.4^{b}
Shrimp yield (ton ha^{-1} $crop^{-1}$)	12.6 ± 0.79^{a}	12.4 ± 0.97^{a}	6.98 ± 0.47^{b}	3.12 ± 0.58^{c}
Shrimp yield (ton ha^{-1} $year^{-1}$)	37.9 ± 2.4^{a}	37.1 ± 2.9^{a}	14 ± 0.93^{b}	6.63 ± 1.1^{c}
Cost per kg of shrimp (RMB kg^{-1})	17.2 ± 0.67^{a}	17.3 ± 0.96^{a}	13.6 ± 0.58^{b}	6.8 ± 0.34^{c}
Profit (RMB ha^{-1} $year^{-1}$)	191,000 ± 1,9000^{a}	183,000 ± 17,000^{a}	72,600 ± 6,300^{c}	99,700 ± 7,400^{b,*}
Profit (RMB ha^{-1} $crop^{-1}$)	63,600 ± 6,500^{a}	61,000 ± 5,600^{a}	36,300 ± 3,100^{c}	47,300 ± 7,500^{b,*}
Feed conversion ratio (FCR)	1.34 ± 0.07^{a}	1.36 ± 0.07^{a}	1 ± 0.09^{b}	1 ± 0.08^{b}
Capital use efficiency	1.29 ± 0.03^{b}	1.28 ± 0.02^{b}	1.38 ± 0.04^{a}	1.36 ± 0.05^{a}
Labor productivity (kg day^{-1})	72.8 ± 24.9^{b}	83.8 ± 27.2^{b}	56.8 ± 23.6^{c}	120.8 ± 30.7^{a,*}

Note: cluster values were presented as mean ± standard deviation. Values in the same row with different superscript letter were significantly different ($P < 0.05$). *Fish production in the polyculture was included to calculate profits and labor productivity.

Table 6. Influential factors of net profits and their coefficients based on multiple linear regression modeling (constant = 31,900;adjusted R2 = 0.932).

Predictors	**Unstandardized coefficient ± Std. Error**	**Standardized coefficient**	***P*-value**
Aeration rate (hrs ha^{-1} yr^{-1})	0.878 ± 0.152	0.435	<0.05
Feeding rate (ton ha^{-1} yr^{-1})	1,600 ± 178	0.473	<0.05
Stocking density (PL m^{-2})	154 ±58.4	0.13	<0.05
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Feeding rate (ton ha^{-1} yr^{-1})	1,600 ± 178	0.473	<0.05
Stocking density (PL m^{-2})	154 ±58.4	0.13	<0.05

Table 7. Influential factors of yields and their coefficients based on multiple linear regression modeling (constant = -7.17; adjusted R^2 = 0.975).

Predictors	Unstandardized coefficient ± Std. Error	Standardized coefficient	*P*-value
Aeration rate (hrs ha^{-1} yr^{-1})	.0001 ± 0	.267	<0.05
Feeding rate (ton ha^{-1} yr^{-1})	.175 ± 0.028	.197	<0.05
Stocking density (PL m^{-2})	.192 ± 0.009	.615	<0.05

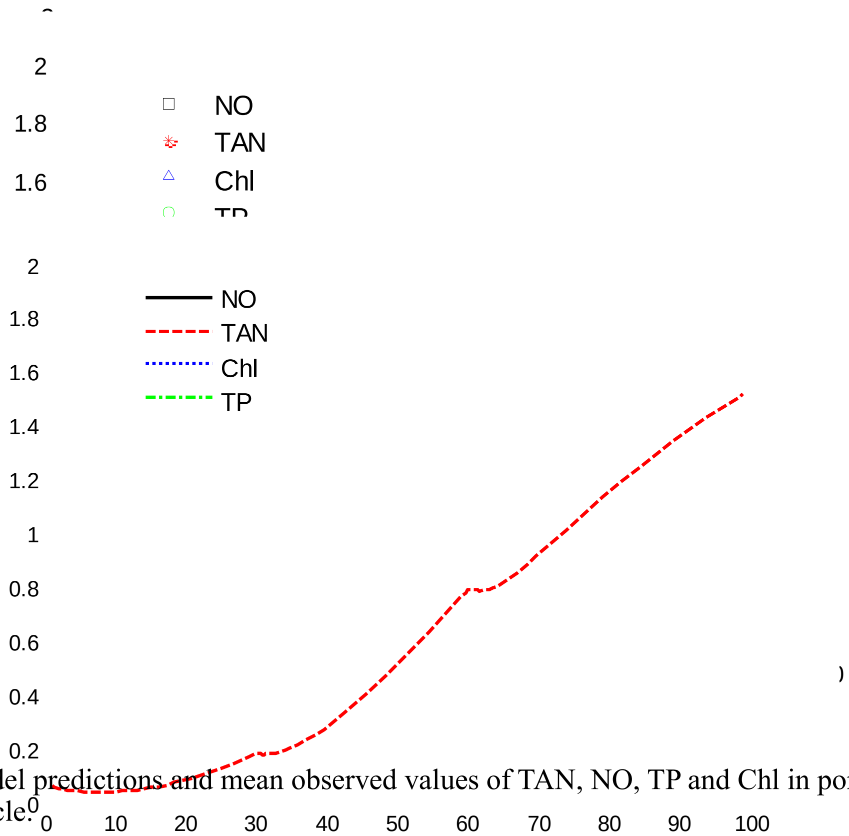

Figure 1. Model predictions and mean observed values of TAN, NO, TP and Chl in pond water over a production cycle.

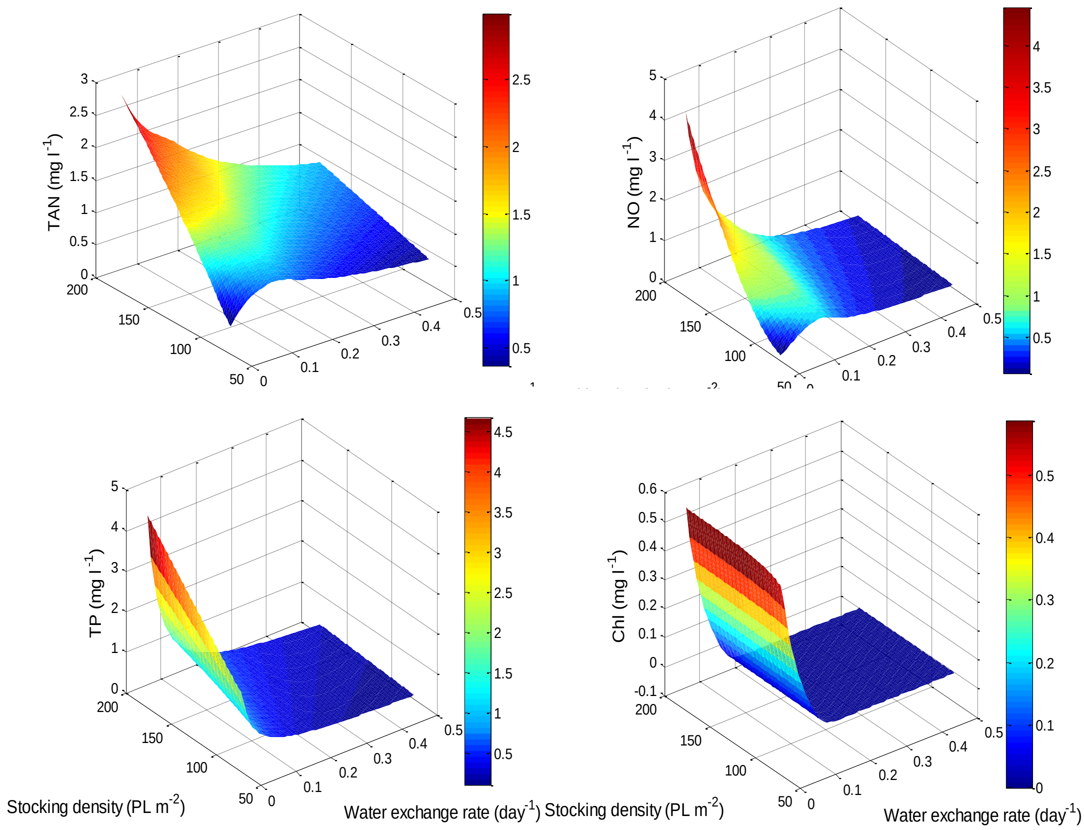

Figure 2. The combined effects of stocking density and water exchange on concentrations of TAN, NO, TP and Chl in pond water at the end of the production cycle.

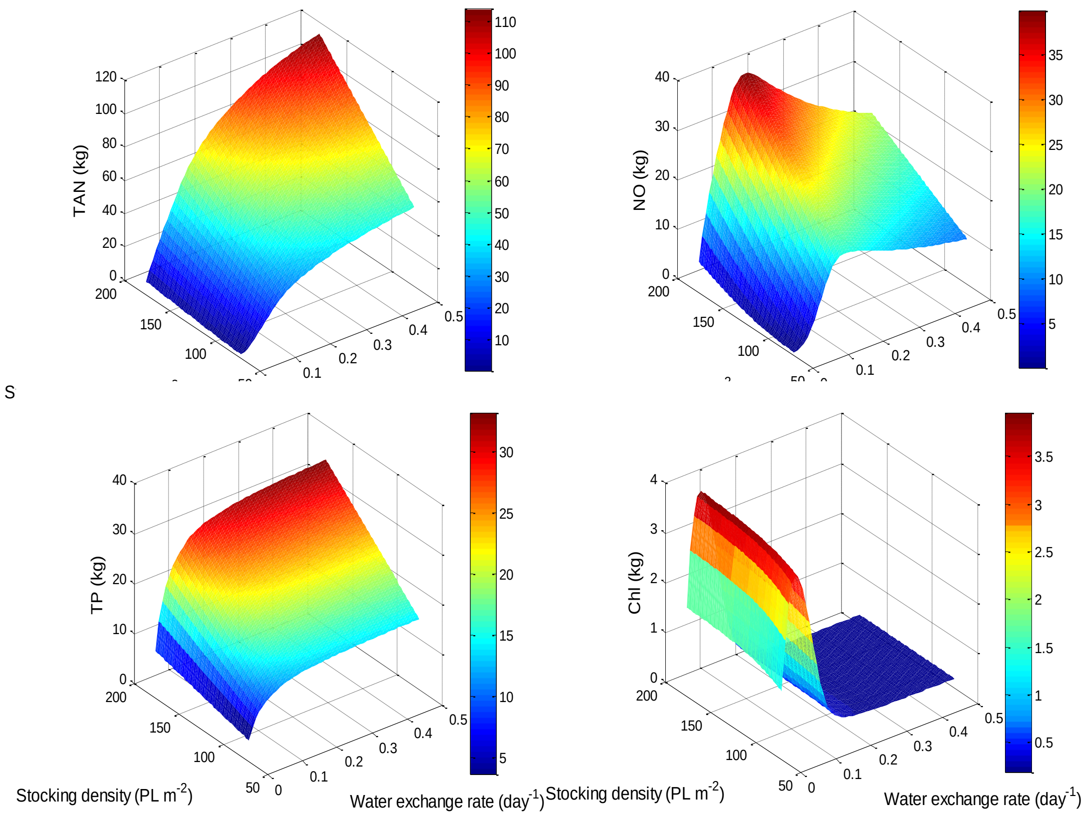

Figure 3. The combined effects of stocking density and water exchange on loading of TAN, NO, TP and Chl from a shrimp pond (pond size = 0.3 ha).

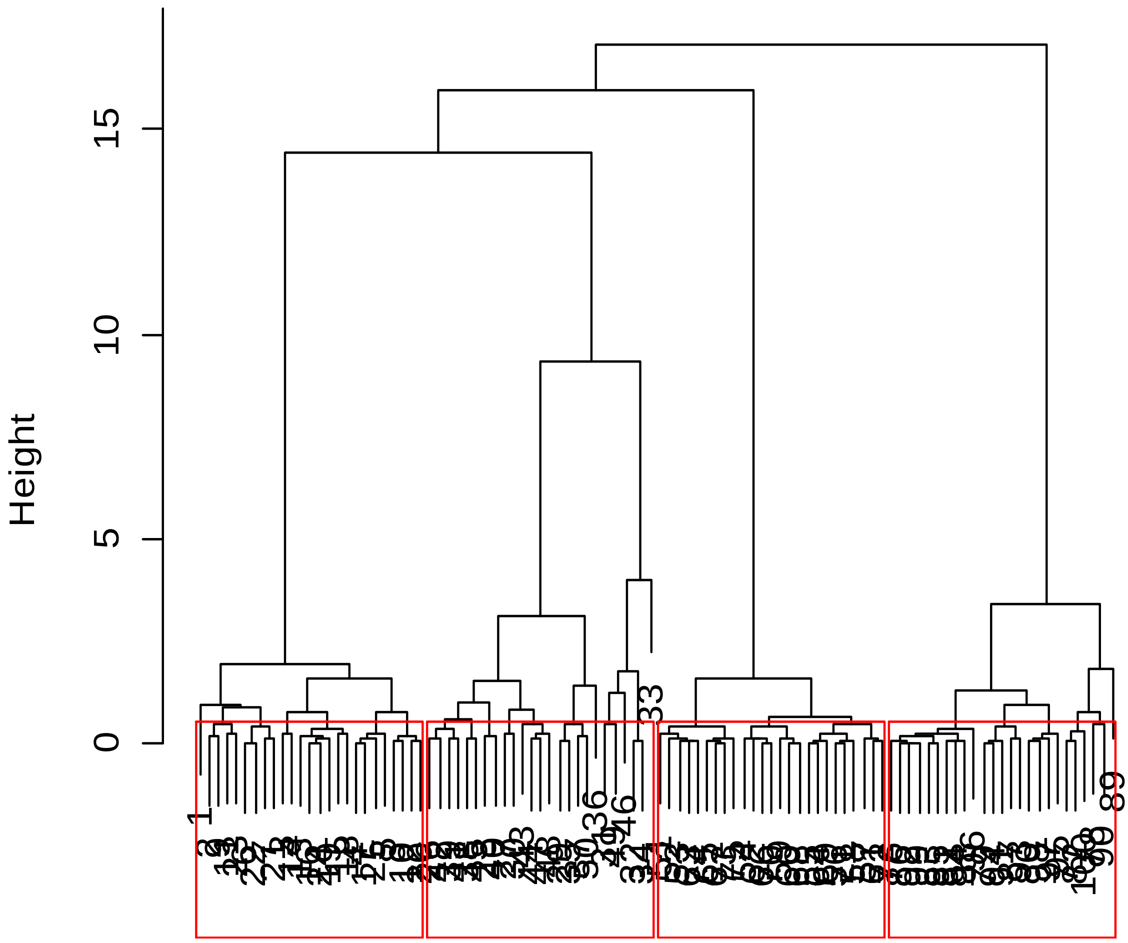

Figure 4. Hierarchical clustering dendrogram with red borders based on Ward's method for estimating numbers of clusters.

Agglomerative Coefficient = 0.99

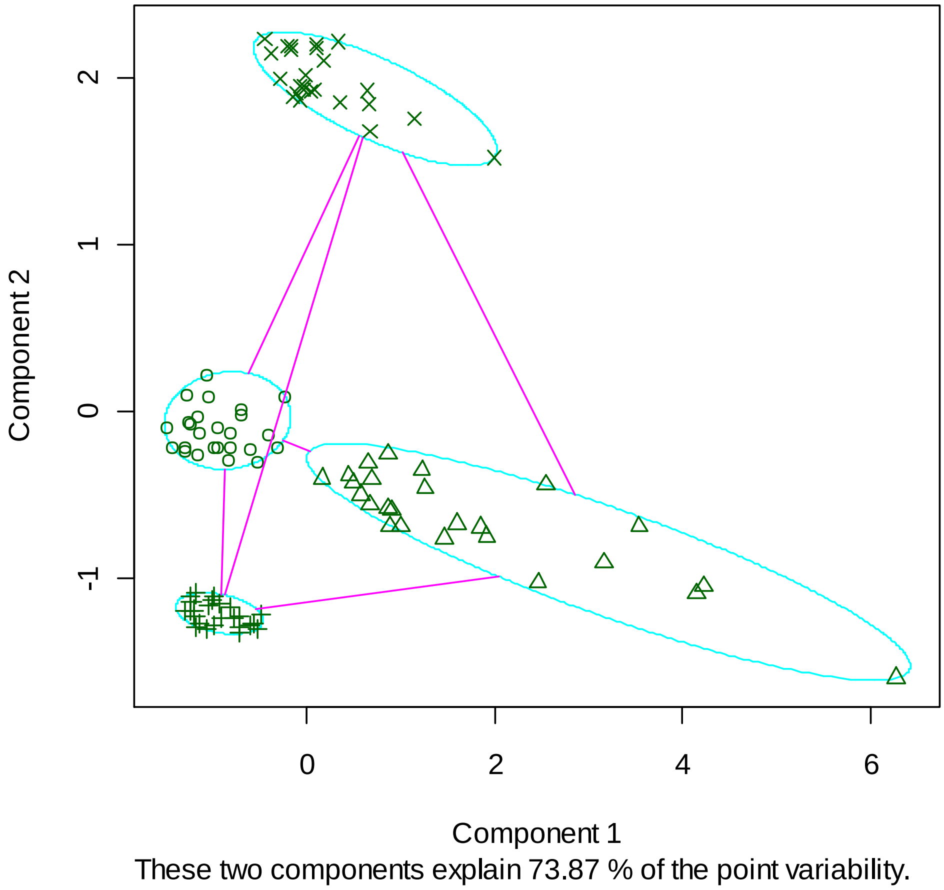

Figure 5. Cluster plot of 4-cluster solution based on non-hierarchical PAM method.

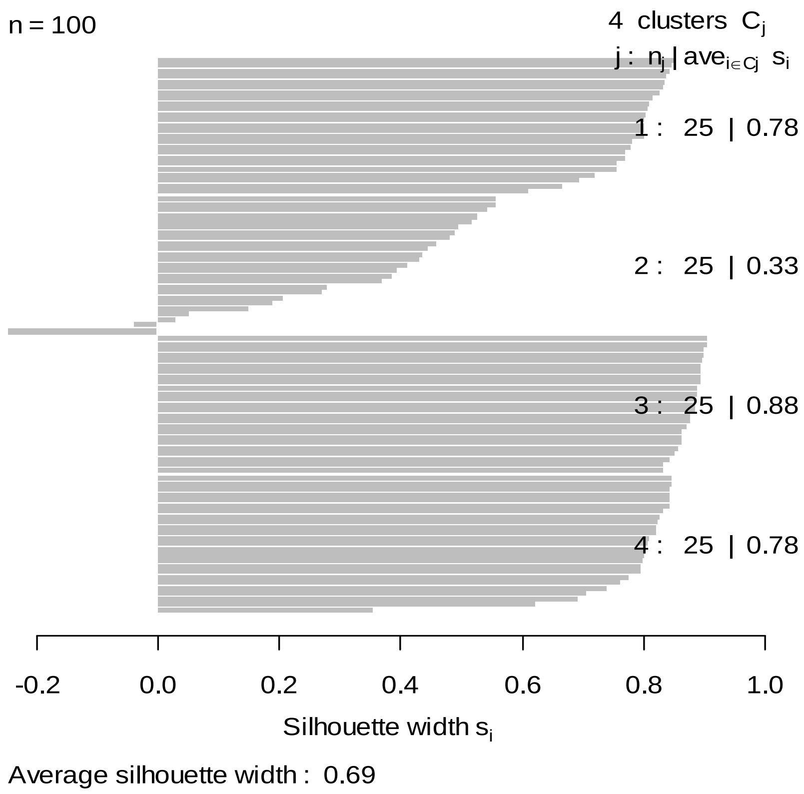

Figure 6. Silhouette plot of 4-cluster solution based on non-hierarchical PAM method

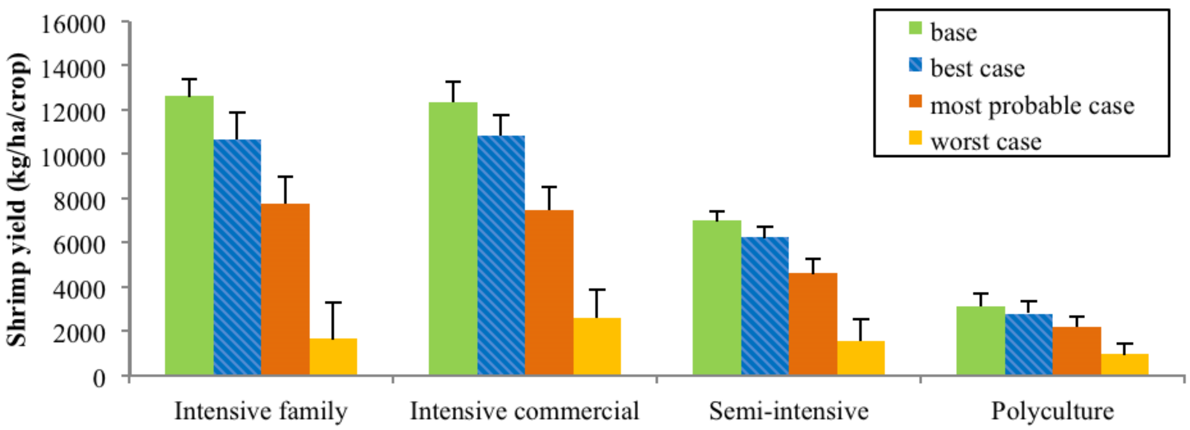

Figure 7. Effects of disease outbreak on shrimp yield given different disease levels (mean + S.D.)