FARMING SHRIMP FOR THE FUTURE: A SUSTAINABILITY ANALYSIS OF SHRIMP FARMING IN CHINA

by

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To My Family

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PREFACE

Chapter 2 - 5 of the dissertation were written as separate papers, published or to be submitted to scientific journals.

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ABSTRACT

The intensification of the shrimp farming industry has generated much concern over its environmental, social and economic sustainability. The objective of this dissertation was to conduct a comprehensive sustainability analysis for Chinese shrimp farming. My results could be utilized to evaluate and improve shrimp production systems in terms of environmental sustainability, economic profitability, and social acceptability.

Life cycle assessment was conducted to evaluate environmental performance of different shrimp farming systems. Intensive systems had higher environmental impacts per unit production than semi-intensive. The grow-out stage contributed on average 95% of the overall impacts, mainly caused by feed production, electricity use and effluents. To produce 1 tonne live-weight of shrimp in China, 38.3 ± 4.3 GJ of energy and 40.4 ± 1.7 tonnes of net primary productivity were required, and 23.1 ± 2.6 kg of SO_2 equivalents (eq), 36.9 ± 4.3 kg of PO_4 eq, and 3.1 ± 0.4 tonnes of CO_2 eq were generated. Changes in feed composition, farm management, electricity generating sources, and effluent treatment may result in future improvement.

Mathematical models were developed to study nutrient dynamics and the effects of management strategies on nutrient dynamics and discharge. Management strategies had significant impacts on nutrient dynamics. Nutrient loading increased with farm intensity. On average, approximately 701 kg N ha^{-1} $cycle^{-1}$ (100 days/cycle) and 176 kg P ha^{-1} $cycle^{-1}$ were unutilized and wasted. Of them, 120 kg N ha^{-1} $cycle^{-1}$ in dissolved form and 62 kg P ha^{-1} $cycle^{-1}$ were discharged with effluents. Moderate stocking density and

reduced water exchange could minimize environmental impacts of pond effluents and achieve high production.

A socioeconomic survey of 100 shrimp farms was conducted to evaluate system profitability, disease risk, and changes in quality of life. Production costs per kilogram of shrimp were highest in intensive systems ($2.70), followed by semi-intensive ($2.10) and polyculture ($1.05) systems. Intensive systems had significantly higher profits ($9,500 ha^{-1} crop^{-1}) than the other two systems (< $7,300 ha^{-1} crop^{-1}). If disease occurred, an average of 78% and 36% of shrimp would die in the worst and most probable cases, respectively. Disease had highest influence on the intensive systems. Quality of life of farmers was significantly improved by shrimp farming.

CHAPTER 1

INTRODUCTION

Aquaculture is of great importance worldwide, serving as an alternative source to traditional food production systems to help accommodate expansion of the human population. Aquaculture production grew at about 10% per year since 1985, compared with 3% for terrestrial livestock and 1.5% for capture fisheries (Diana, 2009). This growth is expected to continue. There is a reasonable prediction that per-capita seafood consumption will increase about 1.5 kg per year by 2025 (FAO, 2004; Diana, 2009). Both population growth and increased individual consumption indicate that seafood products will be gradually more important as an additional food source, and aquaculture will play an important role in that consumption as natural fish stocks continue to decline (Diana, 2009). Global production of farmed shrimp increased from less than 9,000 tonnes in 1970 to more than 3.2 million tonnes in 2008 (FAO, 2010). The driving forces behind expansion of shrimp production include limited and unstable supply from wild fisheries, high profitability, and expanding market demands to import high-quality seafood to the U.S. (which imported 500,000 tonnes of shrimp in 2003), Japan (250,000 tonnes) and Western Europe (500,000 tonnes by France, Italy, Spain, and the UK together) (FAO, 2010). Over 50 countries produce significant amounts of farmed shrimp today. Asia plays the leading role in shrimp farming, accounting for almost 80% of world shrimp culture, mainly from China and Thailand (Mungkung, 2005). Increase of farmed shrimp production is achieved with

intensification of farming systems, often characterized by increased material inputs, energy demands, and effluent discharge (Prein, 2007).

China has become the world's largest producer and second largest exporter of farmed shrimp after Thailand (Mungkung, 2005; FAO, 2010). 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 conceptually classified by stocking density and food source. Shrimp farming systems are generally more intensified than most of fish farming systems. 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. Disease outbreak has become a major concern of this sector and can significantly affect farm profitability (Joffre and Bosma, 2009).

The shrimp farming industry has great economic (significant export earnings) and social (numerous employment opportunities) importance. But shrimp farming has also been criticized for generating negative impacts on the environment, aquatic ecosystems, and human lives in coastal areas (Diana, 2009). These impacts include biodiversity depletion, eutrophication, land modification and food insecurity (Naylor *et al.*, 2000). Shrimp farming usually has a high feed conversion ratio (FCR = feed fed/shrimp weigh gain), with a global average value of 2, which means 2 kg of feed is consumed to produce 1 kg of shrimp (Tacon, 2002). Further growth of shrimp farming with high FCR requires more

fishmeal and hence more marine caught fish, which could cause even higher biodiversity loss (Mungkung, 2005). Development of shrimp farming might also cause shifting of existing livelihoods. The financial risk of shrimp farming, mainly due to inappropriate practices and disease outbreak, has also been noticed, as well as social conflicts generated by competing use of natural resources such as land and water (Paul and Vogl, 2011).

Environmental, economic and social issues have created much concern over how to produce shrimp in a more environmentally benign, economically profitable and socially acceptable manner. These three factors are commonly considered as the triple pillars for sustainability (Wikipedia, 2011). This change can probably be achieved through system optimization by appropriate planning and better management practices, as well as effective regulations. Planning for more sustainable and profitable shrimp aquaculture requires qualitative or quantitative examinations of different alternatives in terms of their environmental impacts, economic benefits and social influence. Despite rising awareness of environmental, economic and social issues, few studies have addressed these issues in a quantitative and balanced manner. Many studies are polarized, either emphasizing economic benefits or mitigating environmental impacts (Bartley *et al.*, 2007). Munkung (2005) has performed a whole life cycle study of shrimp production and consumption to evaluate the environmental sustainability of shrimp aquaculture. However, her research focused on ecological impacts of shrimp aquaculture, with very little coverage of technical and economic aspects, although she described a framework for a comprehensive sustainability analysis covering all three dimensions.

There are many methods proposed for examining sustainability and efficiency of food production systems, including life cycle assessment (LCA), nutrient dynamic modeling

and socio-economic analysis (Bartley *et al.*, 2007). A trade-off exists between environmental costs and economic gains, thus methods that prioritize costs and gains are useful for evaluating system's sustainability. Unfortunately, no single method is robust enough to capture the full suite of environmental impacts and costs associated with food production (Bartley *et al.*, 2007). Each method has its own strength and weakness. Therefore, methods should be combined to make valid and full sustainability analyses. LCA can be used to quantify potential environmental burdens throughout the life cycle of shrimp production. It can be used to calculate the energy and material usage in an overall process. LCA can also provide a framework for evaluating environmental performance and identifying the major processes in energy use, as well as global warming, acidification and eutrophication impacts. Nevertheless, LCA is a less developed and standardized tool for assessing local ecological and socio-economic impacts (Cao *et al.*, 2011). Mathematical modeling has been proven as a useful tool for a better understanding of nutrient dynamics and local environmental impacts of shrimp farming systems (Jimenez-Montealegre *et al.*, 2002; Burford and Lorenzen, 2004). Socio-economic analysis can provide a systematic evaluation of aquaculture activities, and examine impacts of shrimp aquaculture on life quality in rural communities, which in turn can lead to better management strategies towards economic sustainability and social acceptability (Schwantes *et al.*, 2009).

The objective of my dissertation is to conduct a comprehensive sustainability analysis of the Chinese shrimp farming industry from environmental, economic and social perspectives.

The specific research activities include:

1) Perform life cycle assessment of Chinese shrimp farming to evaluate environmental impacts of different production systems and develop strategies for system optimization;

2) Apply mathematical modeling to understand nutrient dynamics in the pond and investigate the impacts of management strategies on nutrient dynamics and effluent discharge;

3) Characterize Chinese shrimp farming systems and conduct an economic and social analysis to evaluate system diversity, profitability and changes in quality of life caused by shrimp farming.

This dissertation is presented in a multiple manuscript format. Chapter 2, 3, 4, and 5 are written as individual papers, including main body and references.

Chapter 2 employs LCA to quantify environmental impacts associated with shrimp production in China from a cradle-to-end perspective. Key stages and hotspots with highest contribution to overall impacts are identified and environmental performance of different farming systems compared. LCA results have been used as a basis to formulate strategies to minimize environmental impacts and promote more sustainable shrimp production.

Chapter 3 extends the scope of Chapter 2 and reviews recent applications of LCA in aquaculture, compares environmental performance of different aquaculture production systems, explores the potential of including biodiversity and socio-economic issues into LCA analysis and examines the potential of LCA to assist in setting criteria for certification and eco-labeling. Chapter 3 highlights LCA methodology and its capabilities

to inform decision makers and other stakeholders who seek to promote more sustainable seafood production and consumption.

As another extension of Chapter 2, Chapter 4 develops mathematical models to characterize nitrogen and phosphorus dynamics in intensive shrimp ponds and evaluate the potential impacts of shrimp farming on the local and regional environment. Models can predict and evaluate the impacts of variation in farming intensity (indicated by stocking density) and water management (indicated by water exchange rate) on water quality and nutrient loading to receiving waters. Models can be used to assist decision-makers in deriving effective management techniques.

After environmental sustainability analysis, Chapter 5 conducts an economic and social analysis to evaluate system diversity, profitability and impacts of shrimp farming on the change of community lives. Multivariate analysis is used to determine typology of Chinese shrimp farming and assess key management practices that have significant impacts on farm profitability. Disease outbreak is modeled to evaluate risk of disease on farm economy. Chapter 5 can provide practical insights for decision makers in order to promote good management practices towards economic sustainability and social acceptability.

Chapter 6 draws the conclusions and summarizes the original contributions of the dissertation. It combines the various sustainability analyses into one overall evaluation of the shrimp industry in China, and considers several topics for future research to move this field of inquiry ahead.

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CHAPTER 2

LIFE CYCLE ASSESSMENT OF CHINESE SHRIMP FARMING SYSTEMS

TARGETED FOR EXPORT AND DOMESTIC SALES

Introduction

Aquaculture is of great importance worldwide, serving as an alternative source to traditional food production systems and helping supply the expansion of human population. Global production of shrimp farming has increased from less than 9,000 tonnes in 1970 to more than 3.2 million tonnes in 2008 (FAO, 2010). Most production occurs in Asia, mainly China and Thailand (Fuchs *et al.*, 1999). International trade of aquaculture products is a means to promote economic growth and alleviate poverty in most developing countries (Diana, 2009). Shrimp is the most traded seafood product (Rivera-Ferre, 2009). In 2008, shrimp aquaculture ranked 2nd of world aquaculture production in value and 4th in quantity (FAO, 2010b). The boom of Chinese shrimp farming has been triggered by growing demand mainly from international markets in USA, EU and Japan. Increase of export-oriented shrimp production is achieved with intensification of farming systems by large commercial companies, which have greater farm size, material inputs, energy demands, and effluent discharge (Prein, 2007). However, the majority of shrimp production in China is still based on traditional techniques from small farms, directed to feed the local population and not for export. The expansion of shrimp farming has generated global concerns over its negative environmental impacts on aquatic ecosystems and human

livelihoods in coastal areas (Diana, 2009). These impacts include biodiversity depletion, eutrophication, land modification and food insecurity. There is debate over whether shrimp farming can be sustainable and how to promote more sustainable export-oriented farming systems. Growing awareness of environmental problems during recent years has led to increasing demand for environmental performance information from different shrimp farming systems.

Evaluating macro-level environmental impacts of shrimp farming systems requires a full evaluation of activities that comprise the whole supply chain. Life cycle assessment (LCA) can be used to make such an evaluation, quantifying potential environmental burdens throughout the life cycle of shrimp production. It can be used to calculate the energy and material usage in an overall process (Diana, 2009). LCA can also provide a framework for evaluating environmental performance and identifying the major processes in energy use, as well as global warming, acidification and eutrophication impacts. It has been widely applied to evaluate seafood products (Mungkung, 2005; Ellingsen and Aanondsen, 2006; Munkung and Gheewala, 2007; Pelletier and Tyedmers, 2007; Aubin *et al.*, 2009; Ayer and Tyedmers, 2009; Pelletier *et al.*, 2009; Pelletier and Tyedmers, 2010). Nevertheless, LCA is a less developed and standardized tool for assessing local ecological and socio-economic impacts. Those impacts could be described quantitatively on the functional unit basis or qualitatively (Pelletier *et al.*, 2007). Impact assessment is generally highly uncertain and less standardized than inventory analysis.

This study employs LCA to quantify and compare cradle-to-destination-port environmental impacts associated with white-leg shrimp (*Litopenaeus vannamei*)
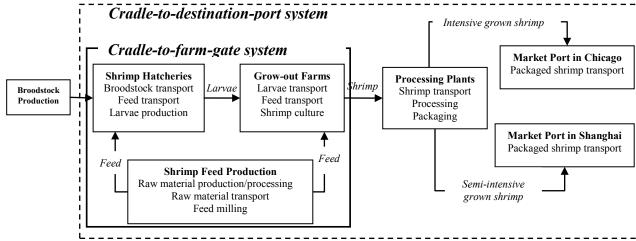
production in China directed toward domestic or export markets in US. Domestic markets are usually linked to traditional semi-intensive farming which mainly use shrimp larvae produced by local broodstock. Export-oriented production is intensive farming which grow shrimp larvae produced by imported broodstock from Hawaii. I are particularly interested in examining biotic resource use, cumulative energy use, global warming, eutrophication, and acidifying emissions associated with shrimp production for both markets, which are typically employed in seafood production (Pelletier *et al.*, 2007). The objectives of this study are to: 1) identify key stages and hotspots with highest contribution to overall impacts and assess the most significant environmental impacts; 2) compare how these two market-oriented production systems (intensive vs. semi-intensive) differ in their environmental performance; 3) evaluate the contribution to overall environmental performance of transporting frozen shrimp products to export markets; 4) use the LCA results as basis to formulate strategies to minimize environmental impacts and promote more sustainable shrimp production.

Results of this study could be used to optimize market-oriented shrimp production systems in terms of environmental sustainability. The quantifiable benefits include direct evaluation of shrimp farming systems to advise regulation and environmental impact mitigation measures for policy makers, to guide shrimp farmers toward implementing good aquaculture practices, and to inform consumers in their awareness and choice for more sustainable consumption.

Methods

System boundary

Global and regional environmental impacts associated with intensive (for export sale) and semi-intensive (for domestic sale) shrimp supply chains were evaluated using LCA following ISO guidelines (ISO, 2006). The main system boundary of my study was from cradle to farm-gate, including feed production, production of larvae at hatcheries, production of marketable-size shrimp at the farm level (Figure 2.1). The transportation of materials at each step was taken into account. Processing and distribution impacts in transporting the processed shrimp from farm gate to final market port were also evaluated to study their significance in a cradle-to-destination-port system (including cradle-to-farm-gate system, processing and distribution). The subsequent wholesale, retail, consumption and disposal of waste were not included. The functional unit was 1 tonne live weight of shrimp for cradle-to-farm-gate and 1 tonne of frozen headless shell-on shrimp product for cradle-to-destination port.

Figure 2.1 Life cycle flow chart and system boundaries for LCA of shrimp produced in China and distributed to domestic (Shanghai) and export (Chicago) markets.

System description

There are mainly two types of hatcheries in China. One is industrial-scale, characterized by high investment, advanced technology, and importing specific-pathogen free (SPF) broodstock from US. This type of hatchery uses high densities and water exchange rates, and produces SPF larvae throughout the year. SPF larvae are characterized by high survival rate, growth rate, and disease resistance. The other type of hatchery is small-scale and family-based, characterized by low investment and technology, using locally domesticated broodstock and producing larvae with lower survival and growth rates.

Farm types are usually differentiated by larvae source, stocking rate, food source and management. Semi-intensive farms usually culture larvae produced by small-scale hatcheries, while intensive farms use SPF larvae produced by industrial-scale hatcheries. Semi-intensive farms use both fertilizers and commercial formulated feed, while intensive farms use only feed. Intensive farms also have higher stocking rates, aerating rates and water exchange rates than semi-intensive ones.

Harvested shrimp are transported directly to processing plants for further processing and packaging. Depending on market requirements, shrimp are processed into different forms such as headless shell-on shrimp, peeled tail-on shrimp, and peeled deveined shrimp. After processing, intensively grown shrimp are exported to international markets in US, Japan and Europe. Shrimp from semi-intensive farms are sold in domestic markets in China. Additional information on system differences is provided in Table A1 in Appendix.

Life cycle inventory (LCI)

The LCI involved onsite data collection for all the relevant inputs and outputs associated with the two studied supply chains. A total of 6 hatcheries and 18 farms which represented different hatchery and farming types were visited to ensure data quality. The operating data for the 18 farms were average values based on the three most recent years of production. Primary operating data were obtained directly from shrimp feed companies, hatcheries, shrimp farms, and processing plants in Hainan Province, China in 2008. Shrimp feed composition modeled in the analysis was obtained through records from local feed companies. In each case, head managers were interviewed with detailed questionnaires. Facility records and appropriate estimations by head managers were used to reduce possible errors. Emissions of macronutrients to water associated with shrimp farming were estimated through nutrient balance modeling. The calculations of nitrogen (N) and phosphorus (P) emissions were based on difference between the amount of nutrients provided to shrimp via feed and fertilizers and the amount assimilated as weight gain (Aubin *et al.*, 2009). Secondary data such as electricity production, extraction and processing of raw materials, and transportation were obtained from published sources or extensive databases within Simapro 7.1 software and modified appropriately to conform to regional conditions whenever possible (see Table A2 in Appendix).

Life cycle impact assessment (LCIA)

LCIA characterizes environmental impacts based on LCI results. The following environmental impact categories were considered: biotic resource use (BRU, net primary productivity as measured in carbon) (Papatryphon *et al.*, 2004; Pelletier and Tyedmers,

2007), cumulative energy use (CEU), global warming (GW), acidification (Acd.) and eutrophication (Eut.). With the exception of biotic resource use, the calculation was processed using data fed into Simapro 7.1 software (PRé, 2008). Acidification, eutrophication and global warming impacts were calculated using the problem-oriented (mid-point) CML2 baseline 2000 method (version 2.04) (PRé, 2008). Cumulative Energy Demand method (version 1.05) was adopted to calculate cumulative energy use (PRé, 2008). Calculation of BRU followed the method described by Pelletier and Tyedmers (2007). Two shrimp supply chains directed to export markets in Chicago (intensive farming) and domestic markets in Shanghai (semi-intensive farming) were modeled respectively and compared. All impacts were calculated per live-weight tonne of shrimp for cradle-to-farm-gate system and per tonne of frozen headless shell-on shrimp for cradle-to-destination-port system.

Comparison of different characterization methods

Base case results from CML2 Baseline 2000 method were verified by adopting two different LCIA methodologies available in Simapro software to test the consistency and reliability of results. One end-point method (Eco-indicator 95) and one mid-point and end-point combination method (IMPACT 2002+) were adopted to compare with the current mid-point method (CML2 baseline 2000). Three common impact categories (Acd., Eut., and GW) which were considered important for aquaculture (Pelletier *et al.*, 2007) were selected as comparison criteria.

Uncertainty & sensitivity analysis

An uncertainty analysis was conducted for environmental impact results based on the set of inventory data collected from 18 different farms (9 farms for each type) to calculate confidence intervals of environmental impacts. Mean and standard deviation (S.D.) of inputs and outputs at the farm level were used to construct 95% confidence intervals. As a comparison, Monte Carlo simulation in Simapro was performed with set stop factors of 0.005 to generate 95% confidence intervals (PRé, 2008) to test uncertainty for all impact categories except BRU. Sensitivity analyses were performed to evaluate possible strategies for environmental performance improvement through scenario modeling.

Results

Life cycle inventory

Detailed information of inputs and outputs for feed production, larvae production at hatcheries, processing, and transportation at each step are reported in Tables A3-A11 in Appendix.

Inputs and outputs to larvae production at two different hatcheries (one was an industrial-scale system using imported broodstock from Hawaii and the other was a small-scale system using domesticated broodstock) varied markedly. With relatively lower larvae production, the small-scale system required higher infrastructure and operational inputs and generated more operational outputs per unit of larvae produced. Only transport and electricity related inputs were higher in the industrial-scale system. This was because broodstock was imported from Hawaii by air and this advanced system

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used more energy for water pumping and aeration to keep shrimp and larvae alive at high density. One tonne of shrimp larvae produced by small-scale hatcheries in China consumed 12 tonnes of feed and 96.5 GJ of electricity, while 8.8 tonnes of feed and 111 GJ of electricity were needed to produce 1 tonne of larvae in industrial-scale hatcheries.

On-farm material and energy inputs and nutrient effluents showed substantial differences per tonne of shrimp produced by each farming type (Table 2.1). Overall, intensive farming had consistently higher on-farm energy and feed use. Higher stocking density and water exchange rates also required more electricity use for aeration and pumping in intensive farming. Relative to semi-intensive systems, on-farm energy use per tonne of shrimp was 470% higher than intensive systems. The amount of feed required to produce one tonne of shrimp varied from 1,600 kg in intensive farming to 907 kg in semi-intensive farming systems. As a result of higher feed usage, farm-level nutrient emissions were also considerably higher in intensive systems. However, with higher stocking density and unit production, intensive farming had lower infrastructure-related inputs, except HDPE liners which were only used in intensive ponds.

Table 2.1 Farm-level inputs and outputs (Mean ± S.D.) for the production of 1 tonne live-weight of shrimp in China in 2008.

Inputs/Outputs	Materials	Intensive farming	Semi-intensive farming
Inputs-infrastructure[1]	HDPE[2] liner (kg)	28.4±3.5	-
	Concrete (kg)	1.95±0.4	1.42±0.4
	Diesel (l)	7.08±1.04	23.9±2.8
	PVC[3] pipe (kg)	1.5±0.5	2.3±0.48
Inputs-operational	Larvae (#)	215,000±9,100	191,000±8,600
	Sea water (l)	12,100±470	13,000±580
	Chlorine (kg)	44.7±3. 8	103 ±7.3
	$CaCO_3$ (kg)	419±57	909±76
	CaO (kg)	195±22	318±36
	Triple superphosphate (kg)	-	28.3±3.8
	Urea (kg)	-	21.2±2.5
	Poultry manure (kg)	-	283±41
	Feed (kg)	1,600±190	970±170
	Electricity (kWh)	2,550±220	548±88
Outputs-operational	Total nitrogen (TN, kg)	66±12	38±3.7
	Total phosphorous (TP, kg)	9±1.6	3.5±0.8

Notes: [1]Including pond and water management infrastructure; [2]high-density polyethylene; [3]Polyvinyl chloride.

Electricity, water, plastic and cardboard packaging and ice were the main material and energy inputs to processing operations. Shrimp out of processing plants was frozen, headless, shell-on and packaged. These frozen packaged shrimp products were transported 2,500 km and 18,500 km by ocean freighter to destination ports in Shanghai and Chicago, respectively.

Life cycle impact assessment

Using life cycle assessment models, contribution analysis focusing on cradle-to-farm-gate shrimp production was conducted to identify the key contributors for each impact category for both farming systems (Table 2.2). Intensive farming created markedly higher environmental impacts than semi-intensive farming in all five categories: acidification (56% higher), eutrophication (49%), GW (48%), CEU (44%) and BRU (39%). Feed (36%-100%) and electricity production (28%-57%) dominated in

all impact categories except eutrophication for both systems in the grow-out stage. Grow-out effluents contributed 83%-88% to eutrophication. By averaging over two farming systems (assuming 85% of farms are semi-intensive and 15% intensive), 1 tonne live-weight of shrimp production in China required 38.3±4.3 GJ of energy, as well as 40.4±1.7 tonnes of net primary productivity, and generated 23.1±2.6 kg of SO_2 eq, 36.9±4.3 kg of PO_4 eq, and 3.1±0.4 tonnes of CO_2 eq.

Environmental impacts of the shrimp supply chains from cradle to destination ports were also evaluated. The results of semi-intensive were normalized to the intensive chain in each category (Figure 2.2a). Semi-intensive systems were 40%-50% lower than intensive systems in all impact categories. Confidence intervals (95%) were presented as error bars (Figure 2.2a), which were calculated as Mean±1.96*S.D. of inventory data at the farm level. Eutrophication showed the greatest variability, while biotic resource use showed the least. Confidence intervals (95%) were also determined by Monte Carlo simulation in Simapro for each category except biotic resource use to evaluate uncertainty (see Figure A1 in Appendix). Eutrophication impact had the lowest uncertainty and cumulative energy use the largest.

Table 2.2 Life cycle impacts (cradle to farm-gate) associated with 1 tonne of live-weight shrimp produced from the two farming systems.
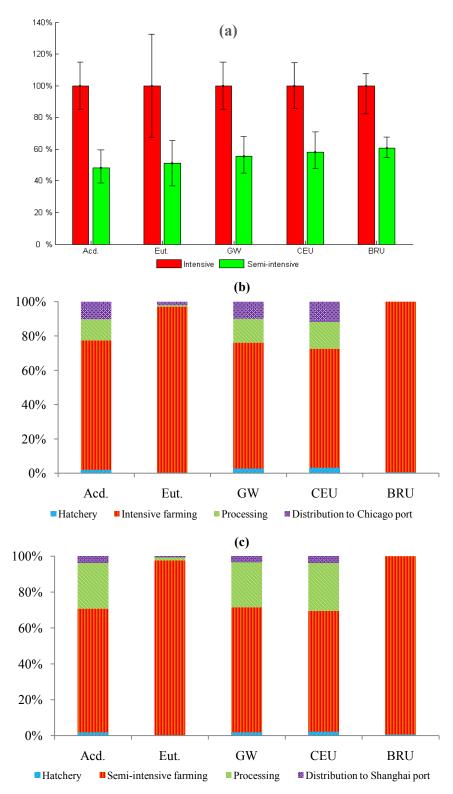
	Acd. (kg SO$_2$ eq)	Eut. (kg PO$_4$ eq)	GW (kg CO$_2$ eq)	CEU (GJ)	BRU (kg C)
Intensive Farming					
Larvae production	1.15	0.23	188	2.72	0
Grow-out infrastructure	0.25	0.02	64.5	2.66	0
Feed production	15.8	6.3	2,110	28.3	60,700
Electricity use	25.2	1.04	2,450	23.2	0
Chlorine	0.24	0.02	48.4	0.94	0
Limestone	0.03	0.004	5.41	0.12	0
Burnt lime	0.55	0.03	270	1.32	0
Grow-out effluents	0	55.3	0	0	0
Larvae transport	0.21	0.03	56.4	1.02	0
Feed transport	0.42	0.07	59.5	0.87	0
Other transport	0.17	0.03	24.5	0.36	0
TOTAL (Mean ± S.D.)	**43.9±4.2**	**63±11**	**5,280±510**	**61.5±6.1**	**60,700±3,900**
Semi-intensive Farming					
Larvae production	0.5	0.1	70.8	1.07	0
Grow-out infrastructure	0.18	0.02	20.5	1.45	0
Feed production	9.55	3.82	1,280	17.1	36,800
Electricity use	5.41	0.22	526	4.98	0
Fertilizer	1.46	1.27	160	3.01	0
Chlorine	0.55	0.04	112	2.16	0
Limestone	0.06	0.01	11.8	0.27	0
Burnt lime	0.9	0.05	441	2.16	0
Grow-out effluents	0	26.7	0	0	0
Larvae transport	0.11	0.02	29.8	0.54	0
Feed transport	0.26	0.05	36.1	0.53	0
Fertilizer and other transport	0.44	0.08	61.9	0.91	0
TOTAL (Mean ± S.D.)	**19.4±2.9**	**32.3±4.7**	**2,750±400**	**34.2±4.9**	**36,800±1,900**

Another contribution analysis was performed to identify subsystems with the highest environmental loads in the two shrimp supply chains (Figure 2.2b, 2.2c). Similar patterns occurred in both supply chains. The grow-out stage showed significantly higher contributions to all impact categories compared to hatchery, processing and transport, and thus it is the key life cycle stage. For cradle-to-destination-port life cycle impacts of shrimp production, grow-out accounted for 69.4% to 96.8% in intensive and 67.4% to 99.3% in semi-intensive systems for each impact category. Processing contributions ranged from 0.9% to 15.6% in intensive and 0.6% to 26.8% in semi-intensive systems.

Although frozen packaged shrimp was transported a long way to destined ports, transportation contributed only 2% to 11.8% in intensive and 0.6% to 3.7% in semi-intensive systems in each impact category. Contributions from larvae production at hatcheries were negligible in both supply chains for all impact categories.

Given the importance of shrimp feed, comparative life cycle impacts of shrimp feed production were evaluated (see Figure A2 in Appendix). The major contributors were fishmeal, wheat flour and feed milling. Fishmeal was the largest contributor to all impact categories other than eutrophication which was dominated by wheat flour. Fishmeal accounted for 44% of acidification, 47% of global warming, 47% of cumulative energy use, and 91% of biotic resource use. Wheat flour contributed 47% to eutrophication.

Figure 2.2 (a) Normalized impacts of the semi-intensive relative to the intensive supply chain. Error bars represent 95% confidence intervals; (b) Life cycle contribution analyses of intensive farming systems from cradle to Chicago port; (c) Life cycle contribution analyses of semi-intensive farming systems from cradle to Shanghai port.

Comparison of characterization methods

Despite differences in characterization methods and parameters between CML2, IMPACT 2002+ and Eco-indicator 95, all three methods gave similar results for acidification and global warming. IMPACT 2002+ predicted much lower eutrophication for both systems compared to the other two methods (see Table A12 in Appendix).

Sensitivity analysis results

I undertook a sensitivity analysis to estimate how global warming would change if the Chinese electricity mix was shifted from coal dominated to less CO_2 intensive energy. Three alternatives were compared to the baseline: 1) baseline, coal-dominated: coal (65.7%), hydropower (25%), natural gas (7.3%), nuclear (2%); 2) natural gas dominated: replace coal with natural gas; 3) nuclear dominated: switch coal to nuclear power; 4) hydro dominated: switch coal to hydro power. Results showed a 25%-50% drop in GW when coal was replaced by hydro or nuclear but only a 12%-25% drop when coal was replaced by natural gas. Similar trends occurred for both farming systems (see Figure A3 and A4 in Appendix).

The effect of feed conversion ratio on environmental performance was modeled for intensive farming systems. Although the average feed conversion ratio (FCR) for the intensive system is 1.6 (1 tonne of shrimp production consumes 1.6 tonnes of feed), surveyed intensive farms had FCRs ranging from 1.4 to 2. I modeled two cradle-to-farm-gate scenarios with FCR at 1 and 1.3 to compare to the baseline FCR at 1.6 (see Figure A5 in Appendix). Lowering FCR would reduce global warming by 8%-16% and biotic resource use by 19%-37%.

I also simulated the effect of replacing fish-derived ingredients with crop-derived ingredients in shrimp feed on environmental performance for intensive farming. Fishmeal and squid meal were substituted with soybean meal, and fish oil with soy bean oil. Three scenarios were modeled: 10%, 30% and 50% substitution (see Figure A6 in Appendix). After substitution, global warming would be 3%-14% lower and biotic resource use 10%-50% lower per tonne of shrimp produced.

Discussion

Although 85% of shrimp farms in China are currently semi-intensive (Biao and Kaijin, 2007) to serve domestic markets, the Chinese government subsidizes intensive farming for export to obtain foreign exchange earnings and promote economic development. The fraction of intensive farming has increased rapidly as a result (Rivera-Ferre, 2009). However, expansion of export-oriented shrimp production can have negative environmental impacts (Rivera-Ferre, 2009). As a result, two important questions arise: 1) Can export-oriented shrimp production be more sustainable? 2) How to promote more sustainable shrimp production (Rivera-Ferre, 2009)?

Comparison of environmental performance

With a total white-leg shrimp production of 1,270,000 tonnes in 2008 (FAO, 2010), the estimated total GHG emissions from Chinese shrimp production would be 4 million tonnes, which was 0.06% of the energy related CO_2 emissions for the entire country (6,534 million tonnes) (EIA, 2010). The estimated total electricity and energy consumption for shrimp production would be 1.1 billion kilowatt hours and 49 million

GJ, 0.036% and 0.052% of the total electricity (3,017 billion kilowatt hours) and energy consumption (88.1 quadrillion Btus) (EIA, 2010) for the country.

Intensive supply chains directed to US markets generated almost twice the environmental impacts of semi-intensive supply chains directed to domestic markets by my modeling results. Intensive chains demanded far more energy and material inputs than semi-intensive chains. Intensive grow out performed significantly worse than semi-intensive grow out, due to higher stocking density, electricity use, feed inputs, and concentrations of nutrients in effluents. Due to higher land footprint and greater use of chemicals and antibiotics, intensive probably outperformed semi-intensive systems in land modification but were worse for food security.

My results confirmed previous seafood LCA studies on shrimp and salmon that environmental impacts were concentrated at the production level, low for other subsystems, and negligible for infrastructure (Mungkung, 2005; Pelletier and Tyedmers, 2010). Following grow-out, processing also contributed substantially to total impacts. In contrast, hatchery and transportation to domestic markets made negligible contributions, which indicated that importing broodstock from Hawaii did not harm environmental performance. Distribution to Chicago port contributed a small but significant fraction to impacts of the intensive supply chain compared to grow-out and processing. Thus local or national consumption of fresh or frozen farmed shrimp without processing and packaging would reduce total environmental impacts substantially.

Strategies for improving environmental performance

Activities that contributed disproportionately to the total environmental impacts during production were identified and could be used to develop regulation goals and mitigation measures to promote more sustainable shrimp production in the future. Feed production, electricity use and pond effluents emerged as 'hotspots' of concern for both farming systems. As one of the hotspots, shrimp feed currently used in China has been criticized for containing too much fishmeal and may potentially lead to depletion of marine fish resources. According to my analysis of shrimp feed production, fishmeal, followed by wheat flour, were the major contributors to all associated environmental impacts. Fish-derived ingredients generally are more impactful per unit mass basis compared to crop-derived ingredients (Pelletier and Tyedmers, 2010). Thus, substitution of fish-derived ingredients with crop-derived ingredients could be a good method to improve environmental performance and reduce associated impacts of shrimp feed. However, appropriate selection of substituted ingredients is critical, since some crop-derived ingredients such as wheat gluten meal are even more impact-intensive compared to some fish-derived ingredients such as menhaden meal (Pelletier *et al.*, 2009). Of course, substitutions must also be palatable to the shrimp and result in similar levels of growth and survival for this analysis to be legitimate. If substitution of fish-derived ingredients lowered shrimp production, the improvement of less impactful feed could be reduced or even outweighed by higher amount of feed used (Pelletier and Tyedmers, 2010). Substitution with crop-derived ingredients could also induce new environmental problems such as deforestation due to soy cultivation (Pelletier and Tyedmers, 2010*)* and exacerbation of eutrophication due to intensive fertilization requirement for wheat

cultivation. Future research exploring alternative shrimp feed formulas should consider how to balance the above issues to achieve a win-win situation.

Shrimp feed conversion ratio is another pivotal environmental performance driver (Pelletier *et al.*, 2009). My studied farming systems had an average FCR of 1.6 for intensive and 0.97 for semi-intensive farms. Since FCR is directly related to biotic resource use and nutrient retention, lower FCR reduces cumulative impacts of shrimp production. FCR is influenced mostly by feed composition, feeding management (Pelletier *et al.*, 2009) and feed quality such as stability in water. If feed composition was the same and feed remained stable longer in water, appropriate feeding regimes would reduce feed loss and dramatically lower FCR.

Electricity use was also identified as a hotspot of shrimp production for two reasons. First, high stocking density and feed inputs cause deteriorated water quality in shrimp farming systems. Frequent aeration and high water exchange rate which consumed electricity were required to maintain water quality. Second, the Chinese electricity generating mix was coal-dominated (Deng and Wang, 2003). To produce 1,000 kWh of electricity in China, total of 889.7 kg of CO_2 eq would be emitted (Deng and Wang, 2003). Of that, 94.7% of the greenhouse gases were contributed by coal (Deng and Wang, 2003). If China could change current electricity mix toward less carbon intensive energy production such as hydro, natural gas or nuclear power, the impact of shrimp production on global warming would be reduced significantly. Even if cleaner energy sources are used, farmers should still adopt good aquaculture practices to minimize total energy use to achieve further improved environmental performance.

Another solution would be installing renewable electricity technologies on-site, such as photovoltaics and wind turbines, if capital costs for small farms are not a barrier.

Farm-level nutrients released in pond effluents were another hotspot. Effluents primarily contain concentrated nutrients, organic matter, ammonia, and suspended solids derived from shrimp metabolites and uneaten food. It is the major contributor to eutrophication. Water quality depends mainly on farming system characteristics, feed quality, and management. As production intensifies, feed inputs and macronutrients retained in pond water also increase (Diana, 2009). Usually about 22.7% of nitrogen and 10.6% of phosphorous inputs from shrimp feed is recovered in shrimp (Páez-Osuna *et al.*, 1999). One tonne live-weight of shrimp production in China can release 0.6 tonne of feces and 0.14 tonne of other metabolites (Jiang *et al.*, 2006). Moreover, my studied farms were outdoor flow-through systems which discharge effluents directly to receiving water bodies without treatment. To promote more sustainable shrimp farming, feeding regimes and stocking rates should be adjusted appropriately so as to not exceed the assimilation capacity of ponds. Policy makers should regulate shrimp farms to treat pond effluents before discharge, which would be necessary for sustainability and the reduction of environmental burdens. However, adopting effluent control could require more energy, and capital costs might be another barrier to adoption by small farms. Governmental intervention such as financial subsidies, tax exemptions, or market price regulation might overcome the capital barrier. Another solution would be shifting to closed recirculating systems to prevent eutrophication issues with discharge. When, reusing water for salmon farming, the closed system outperformed open farming systems in eutrophication emission but all other environmental impact categories were substantially worse (Ayer

and Tyedmers, 2009). This was due to the increased inputs requirements for the recirculating system and lower unit production. There are potential advantages of closed recirculating systems such as less shrimp escapes and improved waste management. The use of suspended microbial floc systems in outdoor flow-though ponds could result in considerable reduction in life cycle impacts compared to indoor recirculating systems using mechanical water treatment. Any of these changes would require further evaluation of environmental performance and profitability to assure more sustainable shrimp production.

The role of intensification in seafood production is the subject of much debate today. More sustainable production systems should incorporate semi-intensive practices to produce shrimp with a lower environmental burden using more natural systems. Semi-intensive has different potential impacts because of factors such as lower production per land unit area than intensive systems. Further research should focus on the relationships between lower intensity aquaculture and biodiversity.

Comparison of life cycle impact assessment methodologies

There are numerous impact assessment methodologies developed in Simapro, such as CML 2000, and IMPACT 2002+ (PRé, 2008). Each method has a different focus which might lead to different results, thus making it difficult to determine which one to choose and which is most likely to approach the true estimation. Results from mid-point methodologies are more precise and detailed, while results from end-point methodologies easier to understand and use for decision making (ISO, 1997). There is no single impact assessment methodology that could be applied to all food production systems

(Mungkung, 2005). I compared different LCIA methods by sensitivity analysis to evaluate the validity of my results. I found no discrepancies for the three most important impact categories for aquaculture. However, data available in the Simapro databases for aquaculture and fisheries products are very limited compared to other industrial products. Moreover, Chinese- or Asian-specific life cycle data are very limited in the Simapro databases which contain data mainly from North America and Europe. Methods are still being developed for assessment of land use, water resources, and biodiversity loss, which limits the validity of my results in these important areas (Nemecek and Gaillard, 2009).

Comparison with other fish or agri-food products

To put the impacts of shrimp production in perspective, I compared my results with other fish and agri-food products (see Table A13 in Appendix). My results were specific to the shrimp case in China with semi-intensive and intensive culture systems, but these systems were also common in the many parts of the world. The specific impacts would differ in each location due to differences in factors such as electrical grid but the general trend would be probably similar. However, due to differences in system boundaries, functional units, and impact assessment methodologies adopted, comparisons could be subjective (Munkung and Gheewala, 2007). Based on CO_2 emissions and energy consumption per kg of product produced, most products such as beef and pork are more GW-intensive and energy-intensive than fish products. Poultry is comparable to fish products in both impact categories, which confirms that poultry is among the most efficient land-based meat products (Ellingsen and Aanondsen, 2006). Beef is the most GW-intensive and energy-intensive among all the food products, as it releases 9 times

more of greenhouse gases and consumes 7 times more of energy compared to an equivalent amount of Chinese farmed shrimp. Among all fish products, Thai farmed shrimp was the most GW-intensive. Farmed salmon is the most energy-intensive, as it requires twice the energy compared of an equivalent amount of Chinese farmed shrimp (Mungkung, 2005; Ayer and Tyedmers, 2009). Tilapia is most efficient of all the food products, probably due to its lower protein needs, higher FCR, and need for less or no aeration (Pelletier and Tyedmers, 2010).

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CHAPTER 3

APPLYING LIFE CYCLE THINKING TOWARDS SUSTAINABILITY IN AQUACULTURE

Introduction

As an alternative food source to wild fisheries, aquaculture shows a great potential to meet the growing demand for seafood and feed the world (Pauly *et al.*, 2002). Global production of aquaculture including fish, molluscs, crustaceans and aquatic plants has increased from less than 700,000 tonnes in 1950 to nearly 70 million tonnes by 2008 which accounts for 50% of the world's fish supply (FAO, 2010). Most production occurs in Asia, which contributes 89% by volume and 79% by value to world aquaculture production. China is the leading producer, accounting for 48% of the world aquaculture total in 2008 (Bostock *et al.*, 2010). Aquaculture has already become the most rapidly increasing food production sector with an average annual growth rate of 6.9% since 1970 (Bostock *et al.*, 2010), and will continue to grow at a significant rate (Diana, 2009). Modern aquaculture is highly diverse, encompassing a great variety of production systems, technologies and more than 310 different farmed species recorded by FAO in 2008 (Pelletier and Tyedmers, 2008; Bostock *et al.*, 2010). Freshwater aquaculture is dominated by carps, tilapia and catfish. Coastal aquaculture primarily comprises salmon, shrimp, oyster, scallop and mussels (Bostock *et al.*, 2010). Production systems range from traditional low intensity such as extensive and semi-intensive to highly intensive systems with different

farming technologies. Closed recirculating and organic systems have emerged as newly developed alternatives to conventional systems.

The expansion of aquaculture has partly been achieved by system intensification, which has drawn criticisms of aquaculture over its environmental, economic and social sustainability. These criticisms include pressure on natural resources such as water, energy and feed, eutrophication caused by effluents, depletion of biodiversity, conversion of sensitive land, introduction of invasive species, genetic alteration of and disease transmission to wild stocks (Diana, 2009), as well as food insecurity. Increasing attention to environmental responsibility of aquaculture underscores the urgent need to understand the environmental footprints of different production systems in order to better manage them to promote more sustainable aquaculture.

Many assessment tools have been developed recently to evaluate environmental impacts of production systems, including risk analysis, ecological footprint, energy analysis and life cycle assessment (LCA). LCA allows comprehensive assessment of relevant environmental impacts along the whole life cycle of a product. It allows one to compile the relative inputs and outputs in an overall process and calculate the potential associated impacts based on a functional unit. Those impacts which cannot be directly measured are calculated by models. Life cycle modeling comprises of four steps: goal definition and scope, inventory, impact analysis and interpretation (ISO, 1998). In the goal definition and scope phase, one should define a system boundary and functional unit for studied systems. In the inventory phase, inputs and outputs for each life cycle stage are quantified and the inventory results are used to characterize resource depletion and environmental and human health impacts in the impact analysis phase. LCA has already

become the leading tool for identifying and comparing the environmental impacts of different food production systems (Pelletier and Tyedmers, 2008).

Currently, there are few methods that can evaluate sustainability of aquaculture in a quantitative and fair way (Diana, 2009). LCA can be used to make such an evaluation in quantifiable terms that are clear indicators of sustainability. In aquaculture, the system boundary is often from cradle to farm gate with the focus on the farm management. Post-farm stages including processing, sale, consumption and waste disposal are less affected by aquaculture practices and thus usually excluded from analysis. LCA can highlight the specific processes responsible for major environmental impacts. For example, phosphate in the pond effluents is the driving force to eutrophication impact. This can be used to inform environmental problems and track hotspots which significantly contribute to overall impacts in aquaculture. LCA also enables analysis of system eco-efficiency and can make suggestions for system/activity improvement, as well as predict environmental outcomes if one activity is changed. However, it should be aware that LCA has limited applications of methodologies.

Although LCA has been widely applied in industrial and agricultural products (Roy *et al.*, 2009; de Vries and de Boer, 2010), LCA-style studies for seafood production systems have been developed for less than a decade. To date, LCA of wild-caught seafood include Swedish cod (Ziegler *et al.*, 2003), Danish fish products (Thrane, 2004a), Spanish tuna (Hospido and Tyedmers, 2005), and Norwegian cod (Ellingsen and Aanondsen 2006). Aquaculture LCAs mainly focus on intensive farming systems (Iribarren *et al.*, 2010) or species with high economic value, including salmon (Ellingsen and Aanondsen, 2006; Ayer and Tyedmers, 2009; Pelletier *et al.*, 2009), shrimp

(Mungkung *et al.*, 2006; Cao *et al.*, 2011), rainbow trout (Grönroos *et al.*, 2006; Aubin *et al.*, 2009; d'Orbcastel *et al.*, 2009), sea bass and turbot (Aubin *et al.*, 2009), tilapia (Pelletier and Tyedmers, 2010), and mussel (Iribarren *et al.*, 2010). There is a growing trend in the use of LCA to study sustainability of seafood production systems (Pelletier *et al.*, 2007).

This article reviews recent applications of LCA in aquaculture, compares environmental performance of different aquaculture production systems, explores the potential of including biodiversity and socio-economic issues into LCA analysis and examines the potential of LCA to assist in setting criteria for certification and eco-labeling. The goal of the review is to highlight LCA methods and capabilities to inform decision makers, producers, researchers, certification and consumer awareness programs, and other stakeholders who seek to promote more sustainable seafood production and consumption.

Assessing sustainability of aquaculture using LCA

I found 10 aquaculture-based LCA studies from peer-reviewed journals or conference proceedings in the last five years. To compare LCA results among selected studies, the functional unit was recalculated to be the same on a mass basis for each scenario. Of all studies reviewed, impact categories commonly used are presented in Table 3.1 with detailed characteristics. Among them, global warming, eutrophication, and acidification and energy use have been employed with highest frequency. Only global warming and ozone depletion have effects on a global scale. Other impact categories manifest regionally on a scale from 100-1000 km or locally to the immediate vicinity

(Thrane, 2004a). However, LCA is still underdeveloped for assessing local ecological impacts such as biodiversity loss, habitat loss, and land use change and socio-economic impacts such as social welfare (Cao *et al.*, 2011).

Table 3.1 Impact categories commonly used in LCA of aquaculture production systems (adapted from Owens, 1996; Pelletier et al., 2007).

Impact category	Characterization factor	Category indicator	Equivalency unit	Spatial	Temporal
Climate change	GWP	CO_2	kg CO_2 eq	Global	Decades/Centuries
Eutrophication	EP	PO_4	kg PO_4 eq	Regional/local	Years
Acidification	AP	SO_2	kg SO_2 eq	Regional	Years
Energy use	EUP	MJ	MJ	Regional/local	Centuries
Biotic resource depletion	BDP	NPP	kg C	Regional/local	Years
Abiotic resource depletion	ADP	Sb	kg Sb eq	Local	Centuries
Ecotoxicity	Ecotoxicity potential	1, 4 DB	kg 1,4DB eq	Local	Hours/Days/Years
Ozone depletion	ODP	CFC	kg CFC eq	Global	Decades/Centuries
Photochemical oxidant	POP	C_2H_4	kg C_2H_4 eq	Regional/local	Hours/Days

Notes: Characterization factors: GWP = Global warming potential; EP = Eutrophication potential; AP = Acidification potential; EUP = Energy use potential; BDP = Biotic depletion potential; ADP = Abiotic resource depletion potential; ODP = Ozone depletion potential; POP = Photochemical oxidant potential. Category indicators: CO_2 = Carbon dioxide; PO_4 = Phosphate; SO_2 = Sulphur dioxide; MJ = Mega Joules; NPP = Net primary productivity; Sb = Antimony; 1,4 DB = 1,4 Dichlorobenzene; CFC = Chlorofluorocarbon; C = Carbon.

Numerous impact assessment methodologies have been developed, such as CML 2000, Eco-indicator 99 and IMPACT 2002+ (PRé, 2008). Each method has a different focus and own special impact categories which might lead to different results. There is no single methodology that comprehensively covers all environmental issues from seafood production. Differences in system boundaries, functional units, and impact assessment methodologies adopted make comparisons of different production systems more difficult (Cao *et al.*, 2011). In spite of this, comparative studies on different systems or products can still be informative towards more sustainable production techniques or consumption. Such comparative studies are not the same as the so-called comparative assertions

disclosed to the public. Although they both require the same functional unit and equivalent methodological considerations for systems being compared, comparative assertions are more rigorous and require external critical review (ISO, 1997).

Intensive, semi-intensive and extensive systems

Traditional aquaculture can be classified mainly by stocking density, feeding management and capital investment. There is a trend towards growing more aquatic crops per unit area in recent years. Extensive systems with lowest unit production have been replaced gradually by semi-intensive and intensive systems. Aquaculture mostly takes place in both semi-intensive and intensive systems in developing countries, while it remains intensive in developed countries (Diana, 2009). Semi-intensive is considered a way of remedying environmental problems associated with intensive farming systems. But does semi-intensive aquaculture at a lower level of intensity using more natural systems truly result in a significant reduction in environmental impacts, especially taking its lower productivity into account? If yes, semi-intensive aquaculture should be promoted to conserve biodiversity and environment. There is very limited published data on the comparison of extensive, semi-intensive and intensive systems.

The most common types of shrimp farms in China are semi-intensive and intensive. Semi-intensive shrimp farming is often different with other traditionally defined semi-intensive aquaculture such as tilapia farming which only relies on natural food. With much higher yields, semi-intensive shrimp farming feed on both commercial feed and fertilizer-based natural food. Criticism of intensification of shrimp farming systems has been focused on high material and energy inputs, and more effluent discharge,

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which might largely increase environmental burdens. My published work (Cao *et al.*, 2011) indicates that, although with higher unit production, intensive shrimp farming systems have almost double the environmental impacts than semi-intensive farming in all studied impact categories (Table 3.2). This is due to higher electricity use, feed inputs, and concentrations of nutrients in effluents. Based on higher land footprint, intensive systems might outperform semi-intensive systems in land modification (Cao *et al.*, 2011). Semi-intensive shrimp aquaculture is environmentally friendlier than intensive farming systems in China. By a comparison of two Chinese shrimp farming systems with a Spanish extensive mussel farming system (Iribarren *et al.*, 2010), extensive mussel system outperformed the other two systems in acidification, eutrophication and global warming per tonne produced. This is probably because mussel culture requires much lower feed inputs than shrimp culture. The result is probably not true for all extensive farming systems due to their lower unit yield. Energy and feed dependence are usually positively correlated with system intensity (Pelletier and Tyedmers, 2007). Aquatic plants such as seaweed culture at a lower intensity usually require the least material and energy inputs. They would be much less environmental damaging compared to fish aquaculture.

Table 3.2 Life cycle impacts (cradle to farm-gate) associated with 1 tonne of live-weight product.

System	Acd. (kg SO$_2$ eq)	Eut. (kg PO$_4$ eq)	GW (kg CO$_2$ eq)	CEU (GJ)	BRU (kg C)	References
Chinese intensive shrimp	43.9	63	5,280	61.5	60,700	Cao *et al.*, 2011
Chinese semi-intensive shrimp	19.4	32.3	2,750	34.2	36,800	Cao *et al.*, 2011
Spanish extensive mussel	4.72	0.4	472	-	-	Iribarren *et al.*, 2010

Notes: Acd. = acidification; Eut. = eutrophication; GW = Global warming; CEU = Cumulative energy use; BRU = biotic resource use.

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Open flow-through and closed recirculating systems

The majority of fish farms, especially in the developing countries, are outdoor flow-through systems which discharge effluents directly to receiving water bodies without treatment. A number of environmental impacts have been recognized. The impacts include: eutrophication and change of fauna in the receiving water bodies; escapement of aquatic crops and their potential ecological and genetic alteration; transfer or spread of disease and parasites to wild stocks; release of chemical hazards to receiving waters (Diana, 2009). Research is ongoing to develop alternatives with an emphasis on closed recirculating systems which may reduce or eliminate the impacts associated with opens systems. By isolating the culture environment from the surrounding ecosystem, closed recirculating systems are designed to grow fish at high densities with zero discharge of effluents. Water is treated to remove toxic wastes and then reused. Reusing water gives farmers better control over the environment, and reduces water consumption and effluent discharge (Bostock *et al.*, 2010). Notable advantages of recirculating systems also include less fish escapes and improved waste management.

Studies by Aubin *et al.* (2009), Ayer and Tyedmers (2009), d'Orbcastel *et al.* (2009) and Pelletier and Tyedmers (2010) employed LCA to compare the environmental performance of open and closed recirculating systems. They investigated how the life cycle environmental impacts would change if open systems shifted to closed recirculating systems (Table 3.3). Overall, the closed recirculating systems outperformed open systems in eutrophication emission and biodiversity conservation but all other environmental impact categories such as global warming and energy use were substantially worse. This was due to greater energy and material requirements for the recirculating system and

lower unit production. Relatively high capital costs would be another barrier for closed recirculating systems to be widely employed and promoted.

Table 3.3 Life cycle impacts (cradle to farm-gate) associated with 1 tonne of live-weight fish produced.

Systems & Species	Location	Acd. (kg SO₂ eq)	Eut. (kg PO₄ eq)	GW (kg CO₂ eq)	CEU (GJ)	BRU (kg C)	ABD (kg Sb eq)	HT (kg 1,4 DB eq)	MT (kg 1,4 DB eq)	References
Net-pen (salmon)	Canada	17.9	35.3	2,070	26.9	-	12.1	639	822,000	Ayer and Tyedmers, 2009
Net-Pen (tilapia)	Indonesia	20.2	47.8	1,520	18.2	2,760	-	-	-	Pelletier and Tyedmers, 2010
Sea cages (Sea bass)	Greece	25.3	109	3,600	54.7	71,400	-	-	-	Aubin *et al.*, 2009
Bag (salmon)	Canada	18	31.9	2,250	37.3	-	13.9	840	574,000	Ayer and Tyedmers, 2009
Flow-through earthen pond (tilapia)	Indonesia	23.8	45.7	2,100	26.5	2,700	-	-	-	Pelletier and Tyedmers, 2010
Flow-through tank (Trout)	France	13.4	28.5	2,020	34.9	28,000	-	-	-	d'Orbcastel *et al.*, 2009
Flow-through raceway (Trout)	France	19.2	65.9	2,750	78.2	62,200	-	-	-	Aubin *et al.*, 2009
Flow-through tank (salmon)	Canada	33.3	31	5,410	132	-	38.1	2,580	3,840,000	Ayer and Tyedmers, 2009
Recirculating tank (Trout)	France	13.1	21.1	2,040	63.2	28,100	-	-	-	d'Orbcastel *et al.*, 2009
Recirculating tank (Arctic char)	Canada	63.4	11.6	10,300	233	-	72.5	54,400	6,510,000	Ayer and Tyedmers, 2009
Recirculating (Turbot)	France	48.3	77	6,020	291	60,900	-	-	-	Aubin *et al.*, 2009

Notes: Acd. = acidification; Eut. = eutrophication; GW = Global warming; CEU = Cumulative energy use; ABD = abiotic depletion; HT = human toxicity; MT = marine toxicity.

Conventional and organic systems

A growing number of consumers place emphasis on seafood safety issues, animal welfare and environmental concerns. Organic aquaculture is becoming increasingly important as consumers become more environmentally aware and demand for more secure seafood. Organic aquaculture is considered as one of the most promising alternatives for reducing environmental burdens associated with intensive farming (EU, 2007). It is defined as an overall system of farm management and food production that

combines best environmental practices, a high level of biodiversity, preservation of natural resources, application of high animal welfare standards and a production method in line with the preference of certain consumers for products produced using natural substances and processes (EU, 2007). Organic aquaculture is often described as superior to conventional farming in that it relies largely on own internal resources and thus consume less external materials and energy. Prohibition on use of man-made artificial chemicals in organic farming markedly reduces ecotoxicity potentials and also conserves biodiversity. Organic products usually have great market opportunities and stable prices in export markets. Despite the rapid growth of organic agriculture production, organic aquaculture is newly developed and still in its early stage (Mente *et al.*, 2011). This is due to diversification of cultured species, obstacles to implementing some organic practices such as complete chemical prohibition and fishmeal substitution, as well as lack of unified certification standards and criteria (Mente *et al.*, 2011). Moreover, some organic farming systems have lower yield and their requirements to adopt organic practices such as using organic feed ingredients may reduce farm eco-efficiency and cause more environmental problems (Pelletier and Tyedmers, 2007). The question arises whether organic farming is really less environmental damaging once lower yields and all changes in practices are considered. LCA can be used to answer this question and provide basis for certification and eco-labeling of aquaculture to indicate the environmentally preferable products and systems.

Mungkung conducted an LCA study for shrimp farming in Thailand and compared life cycle impacts of conventional intensive method to organic as well as other transitional systems (Table 3.4) (Mungkung, 2005). Organic shrimp farms in Thailand

were characterized by operation at lower stocking density with best available organic inputs and complete elimination of man-made artificial chemicals and antibiotics. Conventional intensive systems were managed at high stocking rate and high inputs aiming for high productivity. Overall, the conventional intensive farm showed the highest impacts per tonne produced for all impact categories, except for eutrophication which was highest for the organic farm. The significantly higher impacts from conventional intensive farms were caused by high energy inputs, feed use, and chemical use. The organic system in her study was identified as the more environmentally sustainable practice.

Table 3.4 Life cycle impacts associated with 1 tonne of products.

Product	Acd. (kg SO$_2$ eq)	Eut. (kg PO$_4$ eq)	GW (kg CO$_2$ eq)	ABD (kg Sb eq)	MT (kg 1,4 DB eq)	BRU (kg C)	EU (GJ)	References
Conventional intensive shrimp	18.5	10.6	5,210	91.3	475,000	-	-	Mungkung, 2005
Organic shrimp	3.77	11.5	901	19.5	61,300	-	-	
Conventional salmon feed	12.6	5.3	1,400	-	60,700	10,600	18.1	
Partial-organic salmon feed	11.8	4.9	1,250	-	61,100	10,600	17.1	
All-organic salmon feed	24.6	6.7	1,810	-	63,300	45,100	26.9	Pelletier and Tyedmers, 2007
All-organic salmon feed with substitutions	6.9	2.3	690	-	47,600	6,300	9.86	

Notes: Acd. = acidification; Eut. = eutrophication; GW = global warming; CEU = Cumulative energy use; ABD = abiotic depletion; MT = marine toxicity; BRU = biotic resource use; EU = energy use.

Pelletier and Tyedmers (2007) studied organic salmon farming and concluded that use of organic crop ingredients and fisheries byproducts did not reduce the environmental impacts of feed production for all impact categories considered in their study. They indicated that compliance with current organic standards in salmon farming would rather result in markedly higher environmental burdens with respect to energy use, global

warming, ecotoxicity, acidification, eutrophication and biotic resource use. They suggested that substitution of animal-derived ingredients with plant-based ingredients in fish feed could probably solve this dilemma. It also depends on what plant ingredients used for substitution. Some highly processed plant ingredients such as wheat flour may as environmental damaging as fish-derived ingredients or even result in more environmental burdens in some impact categories such as eutrophication. This is due to concentrated fertilizer use during cultivation and intensive energy and water use during processing. Genetically modified (GMO) soybeans are competing with conventional soybeans to replace animal-derived ingredients in the fish feed in some countries. Organic aquaculture prohibits use of any GMO ingredients. The substitution of animal-derived ingredients with plant ingredients should be further evaluated. More research and case studies are needed to test if the substitution satisfies the nutrition requirement of fish and does not harm fish growth. Some species with high economic value such as shrimp and salmon require higher protein level in the feed. Substitution of animal-based protein with plant protein may result in lower growth rate. Pelletier and Tyedmers (2007) also pointed out that impacts on land use would be greater in organic systems due to lower yields. Optimizing organic farming to achieve higher yields could solve this problem.

Monoculture and polyculture systems

As one of integrated systems, polyculture has been developed as an alternative model to counter the problems such as disease vulnerability and low feed efficiency caused by monoculture. Polyculture systems have higher levels of biodiversity and

usually gain more economic profits. But is polyculture superior to monoculture in terms of environmental sustainability?

Based on a published LCA study on polyculture (Baruthio *et al.*, 2009), potential impacts per tonne of all products from polyculture with freshwater prawn as the main species, prawn from polyculture, and marine shrimp from monoculture were compared (Table 3.5). Results showed that polyculture performed better in terms of global warming and energy use, but not in terms of acidification and eutrophication compared to shrimp monoculture. By economic allocation (proportion of impacts is allocated to each polyculture species based on its market value), impacts per tonne of prawn from polyculture were higher than per tonne of mono-cultured shrimp. Comparative results indicated that the polyculture system was less environmentally sustainable than monoculture in this case.

Table 3.5 Life cycle impacts associated with 1 tonne of products.

System	Country	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	References
Shrimp (monoculture, average value)	China	32	48	4,020	48	Cao *et al.*, 2011
All products (prawn, tilapia, milkfish, crab)	Philippines	34	129	3,550	46	Baruthio *et al.*, 2009
Prawn (from Polyculture and calculated by economic allocation)	Philippines	48	172	5,110	67	Baruthio *et al.*, 2009

Notes: Acd. = acidification; Eut. = eutrophication; GW = global warming; CEU = Cumulative energy use.

Geographical comparisons

Ongoing efforts have been devoted to manage environmental performance of food production from local through regional and global scales. Pelletier *et al.* (2009) presented a global-scale comparison of farmed salmon using LCA (Table 3.6). They evaluated environmental burdens associated with salmon farming in Norway, the UK, Canada, and

Chile. They found that impacts were lowest per unit production for Norwegian production in most impact categories, and highest for UK farmed salmon. These were mainly due to differences in feed composition and feed utilization rate among regions. Greater biotic resource use in Norway and the UK resulted from higher inclusion rates of fish-based inputs such as fish meals and oils derived from high trophic level species. US farmed shrimp (Sun, 2009) had highest impacts on acidification, global warming and energy use, but it had lowest impact on eutrophication. This was due to US shrimp was produced in closed indoor system which used more materials and energy but effluent water was treated and reused. Sometimes, different electricity generating files among regions might be another pivotal environmental performance driver. Electricity generating mix of many developing countries such as China and India is still coal-dominated (Deng and Wang, 2003). If the electricity mix could be changed toward less carbon intensive energy production such as hydro, natural gas or nuclear power, the impact on global warming would be reduced significantly.

Table 3.6 Life cycle impacts (cradle to farm-gate) associated with 1 tonne of live-weight fish produced.

Countries	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	BRU (kg C)	References
Norway (salmon)	17.1	41.0	1,790	26.2	111,000	
UK (salmon)	29.7	62.7	3,270	47.9	137,000	
Chile (salmon)	20.4	51.3	2,300	33.2	56,600	Pelletier *et al.*, 2009
Canada (salmon)	28.1	74.9	2,370	31.2	18,400	
China (shrimp)	43.9	63	5,280	61.5	60,700	Cao *et al.,* 2011
US (shrimp)	50.6	1.5	5,910	99	-	Sun, 2009
Thailand (shrimp)	18.5	10.6	5,210	-	-	Munkung, 2005

Notes: Acd. = acidification; Eut. = eutrophication; GW = global warming; CEU = cumulative energy use; BRU = biotic resource use.

Life cycle comparison of agri-food and seafood

Seafood is an alternative protein source to agricultural livestock products. Application of LCA to seafood products is a recent phenomenon compared to agri-food and industrial products (Pelletier *et al.*, 2007). The unique media of aquaculture presents new challenges for LCA. It is interesting to use well studied agri-food products for bench-marking when assessing environmental impacts of seafood production. Comparison of environmental performance of agriculture and aquaculture products would also be in demand for certification and eco-labeling to guide purchasing decisions for more sustainable consumption. Several studies have been conducted to rank the environmental performance of different agri- and aqua- food products (Ellingsen and Aanondsen, 2006; Mungkung *et al.*, 2006; Williams *et al.*, 2006; Mungkong and Gheewala, 2007; Ellingsen *et al.*, 2009).

Results from several recent studies are summarized and compared in Table 3.7. Based on current listing, agri-food products except chicken are usually more CO_2-intensive and perform worse in acidification and eutrophication than seafood products from both capture fisheries and aquaculture. Beef is most CO_2-intensive and has the highest impacts in acidification and eutrophication. Beef production also uses more land than aquaculture-based seafood. These data indicate that wild-caught seafood, followed by farmed seafood, is more energy-intensive than agri-food. Wild-caught seafood also has the highest impact on land use.

However, due to differences in system boundaries, functional units, allocation procedures and other methodological nuances, comparisons between LCA studies could be subjective and should be made with caution (Cao *et al.,* 2011; Heller and Keoleian,

2011; Mungkong and Gheewala, 2007). With these cautions, comparisons could be made on weight- or protein-basis. Since the main function of seafood is to provide nutrients, Mungkong and Gheewala (2007) proposed to compare different products based on the nutritional values gained from per kg of products, rather than directly compare on weight- or protein-basis. Comparison of different food products with different value chains will be very complicated. Thus, it is necessary to develop a standardized impact assessment methodology to get a true basis for comparison in the future studies (Ellingsen *et al.*, 2009).

Table 3.7 Environmental impact comparison of different food products per tonne of product.

Products	Location	GW (kg CO$_2$ eq)	Acd. (kg SO$_2$ eq)	Eut. (kg PO$_4$ eq)	CEU (GJ)	Land (1000m^2)	References
Beef	UK	25,300	708	257	40.7	38.5	Williams *et al.*, 2006
Pork	UK	6,360	395	100	16.7	7.4	Williams *et al.*, 2006
Chicken	UK	4,570	173	49	12	6.4	Williams *et al.*, 2006
Farmed shrimp (average)	Asia	5,250	31	37	54	2.2	Mungkung, 2005; Cao *et al.*, 2011
Farmed salmon (average)	Europe	2,450	22.4	51.7	43.3	6	Ellingsen and Aanondsen, 2006; Pelletier *et al.*, 2009
Farmed trout (average)	France	2,270	15.2	38.5	58.8	-	Aubin *et al.*, 2009; d'Orbcastel *et al.*, 2009
Wild-caught cod (average)	Europe	3,000	-	-	81.3	1,390	Ellingsen and Aanondsen, 2006; Mungkong and Gheewala, 2007
Wild-caught tuna	Spain	1,800	24	3.7	-	-	Hospido and Tyedmers, 2005

Notes: GW = global warming; Acd. = acidification; Eut. = eutrophication; CEU = cumulative energy use.

Modeling biodiversity loss in LCA

Biodiversity loss is perhaps currently the most serious environmental problem. Global biodiversity is suffering a sharp decline and continuing at an alarming rate (Curran *et al.*, 2011). The major causes of aquatic biodiversity loss are invasive species, habitat loss, pollution, and overfishing for fishmeal species associated with aquaculture (Diana, 2009). Current aquaculture systems now have mostly negative impacts on aquatic biodiversity. None of them is truly sustainable from a biodiversity perspective (Diana, 2009). Impacts arise from resource consumption, land modification, and waste generation. Diana (2009) listed five most important effects of aquaculture on biodiversity, including escapement of aquatic crops and their invasive potentials, effluent effects on water quality, conversion of sensitive land, inefficient resource use, and spread of diseases and parasites. Therefore, it is essential to assess biodiversity loss caused by aquaculture and examine the opportunities for better protection of aquatic biodiversity. Biodiversity should be included as one of the most important impact indicators of sustainability.

Five direct drivers of biodiversity loss have been identified by the Millennium Ecosystem Assessment in 2005 (MA, 2005). They are habitat change, climate change, invasive species, pollution, and overexploitation of wild populations. Although the development and inclusion of biodiversity in LCA has been ongoing for more than a decade, many methodologies in LCA are still in their infancy (Curran *et al.*, 2011). To date, three of five drivers of biodiversity loss have been treated in LCA to some degree, including habitat change, climate change and pollution. They have been developed into impact categories of land use, water use, global warming, eutrophication, acidification

and ecotoxity. However, land use (m^2) in LCA does not characterize the impacts on biodiversity. A new method for evaluating the impacts on biodiversity from land use in agricultural LCA has been proposed with a focus on species richness (Schmidt, 2008). Two drivers including invasive species and overexploitation are still completely missing in the LCA framework (Curran *et al.*, 2011). A number of complete or ongoing studies are attempting to include them quantitatively on the functional unit basis or qualitatively into an expanded LCA framework (Pelletier *et al.*, 2007; Jeanneret, 2008; Alkemade *et al.*, 2009). Many novel impact categories have been developed but not yet scrutinized. Pelletier and his colleagues (2007) also suggested impact categories in agricultural LCAs can provide a basis for impact category development for seafood. To meaningfully characterize biodiversity in LCA, Curran *et al.* (2011) offered two recommendations for future research. First, the methodological shortcomings should be addressed. Then, data representative of distribution of global biodiversity and its pressures should be acquired. Integrating the missing drivers and impact factors of biodiversity could further enhance the credibility of sustainability assessment in LCA (Curran *et al.*, 2011).

Using LCA for certification and eco-labeling

Certification and eco-labeling systems for aquaculture are used to identify sustainable seafood products based on their relative environmental performance. They are a form of sustainability measurement which integrates environmental concerns into aquaculture sector and intend to direct consumers towards more sustainable food consumption. They are a form of sustainability measurement which integrates environmental concerns into the aquaculture sector. Certification and eco-labeling intend

to prevent misleading advertising, provide producers with market-based incentives and direct consumers towards more sustainable food consumption. Three types of labeling schemes have been defined in the ISO 14020 family (ISO, 2000): Type I is a multi-attribute label developed by a third party; Type II is a single-attribute label developed by the producer; Type III is an eco-label whose awarding is based on a full life-cycle assessment.

At present, certified and eco-labeled food products represent one of the fast growing food markets, with an growth rate at 20%-25% per annum (Pelletier and Tyedmers, 2008). The rapid development of diverse certification and eco-labeling systems underscores the need to standardize criteria to provide producers with clear guidelines and reduce consumers' confusion (Pelletier and Tyedmers, 2008). There are now many certification initiatives and consumer awareness programs focusing on food safety, animal welfare, environmental protection and social risk assessment standards. However, few of them are life-cycle based and fully cover all relevant environmental issues. Developing robust measures of sustainability and its assessment tools have been highlighted by the World Wildlife Fund (WWF) aquaculture dialogues (Bostock *et al.,* 2010). LCA is one of the key approaches which can provide a relatively comprehensive measure of the sustainability in the seafood sector to inform certification and eco-labeling criteria. It helps to identify key environmental impacts in the product life cycle which can be used as certification or eco-labeling criteria (Mungkung *et al.*, 2006). Mungkung and colleagues (2006) identified abiotic depletion, global warming and eutrophication as key environmental impacts for shrimp aquaculture which could be covered by eco-labeling criteria. Other important impacts including depletion of wild broodstock, impacts of

trawling for fishmeal species on marine biodiversity, the choice of suitable farm sites, disease spread and release of invasive species could not be quantified by traditional LCA. They can be included as 'hurdle criteria' and qualitatively described in the expanded LCA.

Use of LCA for setting certification and eco-labeling criteria is still very much limited, since socio-economic impact categories are still under development in the LCA framework. Some economic and social indicators at each life cycle stage were proposed for assessing the sustainability of agri-food systems (Heller and Keoleian, 2003), which could be also utilized for assessing seafood production systems. Those indicators include land conversion rate, farm profitability, average wages, health benefits, quality of life and worker satisfaction (Heller and Keoleian, 2003). However, methodologies for the integration of social and economic sustainability through a life cycle approach are still in their early stages. There are increasing efforts working on the integration of social and economic aspects into the LCA framework (Kruse *et al.*, 2009). For instance, life cycle costing has often been employed to address economic issues. Guidelines for social life cycle assessment have also been developed to address social issues. However, practical applications of social life cycle assessment are very limited. Future development and refinement of those economic and social sustainability indicators are needed.

Conclusion

An increasing number of LCA studies of aquaculture have been published. This indicates that LCA is an appropriate means and will become a mainstream tool to evaluate global and local environmental impacts of seafood production systems. As a

systematic approach, LCA can evaluate sustainability of aquaculture systems quantitatively from a cradle-to-end perspective. By assessing system performance, it presents a useful basis for system improvement in terms of environmental sustainability and development of certification or eco-labeling criteria. However, existing LCA methods are not capable of quantifying local ecological and socio-economic impacts, which limits its ability and future application. More efforts should be given to adapt the tool to aquaculture applications, as well as integration of current missing (such as biodiversity) or immature (such as socio-economic) impact indicators for more comprehensive evaluations of system/product sustainability. Overall, LCA is a useful tool and has great potential in assisting decision making for more sustainable seafood production and consumption.

Comparative LCA studies indicate that farming systems with relatively lower intensity using more natural systems are more environmentally friendly. Semi-intensive farming outperforms intensive farming systems. Closed recirculating systems outperform open systems in eutrophication emission and biodiversity reservation but all other environmental impact categories such as global warming and energy use are substantially worse. Polyculture appears not superior to monoculture in terms of environmental sustainability. All current production systems generate environmental burdens and no system or seafood product is really environmentally sustainable. Organic farming with low intensity seems to be a promising system if animal-derived ingredients are substituted with proper plant-based ingredients in the feed. By comparing captured and farmed seafood with agri-food products, agri-food products except chicken are usually more CO_2-intensive and perform worse in acidification and eutrophication than seafood

products. Beef is the most CO_2-intensive and generates the highest impacts in acidification and eutrophication. Wild-caught seafood is more energy-intensive than farmed seafood and agri-food. More comparative studies are needed to benchmark different aquaculture production systems and their seafood products to promote developing more sustainable aquaculture production systems. But comparisons and interpretations should be done with caution, due to differences in system boundaries, functional units and other methodological nuances.

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CHAPTER 4

MODELING THE EFFECTS OF MANAGEMENT STRATEGIES ON NUTRIENT DYNAMICS IN INTENSIVE SHRIMP PONDS IN CHINA

Introduction

Intensification of the shrimp farming industry has generated global concerns over its negative environmental impacts caused by unsustainable management (Naylor *et al.*, 2000; Casillas-Hernández *et al.*, 2006). 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.

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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 my survey (Chapter 5), 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 (Funge-Smith and Briggs, 1998; Jackson *et al.*, 2003; Xia *et al.*, 2004; Casillas-Hernández *et al.*, 2006). 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 (Jimenez-Montealegre *et al.*, 2002; Burford and Lorenzen, 2004). 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 (Lorenzen *et al.*, 1997; Montoya *et al.*, 1999; Burford and Lorenzen, 2004). However, the dynamics of P flow in intensive shrimp ponds have not received much attention (Montoya *et al.*, 2000).

The objective of this study was to characterize N and P dynamics in intensive shrimp farming over a complete production cycle. Mathematical models of N and P dynamics were developed based on previous models built by Lorenzen et al. (1997) and Burford and Lorenzen (2004). Models were calibrated for an intensive commercial farm in China and used to predict and evaluate the impacts of variation in farming intensity (indicated by stocking density) and water management (indicated by water exchange rate) on water quality and nutrient loading. Results of the study could inform stakeholders the potential impacts of shrimp farming on the local environment and also assist farmers in deriving better management techniques for more sustainable production.

Methods

Field and laboratory analyses

During April-July 2010, field sampling 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 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.
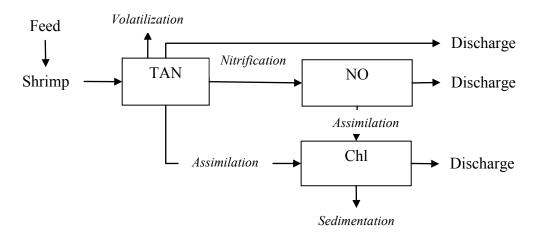
Total ammonia-N (TAN), nitrite-N (NO$_2$), nitrate-N (NO$_3$), total Kjeldahl nitrogen (TN), dissolved reactive phosphorous (DRP), total phosphorous (TP), Chlorophyll α (Chl) and total suspended solids (TSS) were analyzed. The determination of TAN, NO$_2$, NO$_3$, DRP, Chl and TSS were conducted according to standard methods (Strickland and Parsons, 1972; APHA, 1989). TN and TP were 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).

Mathematical 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). For intensive shrimp ponds, water preparation was done before use to ensure that zooplankton and benthos were all killed. Thus, there were not complex benthic organisms

in the water. Shrimp were assumed to feed on the commercial feed only. 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).
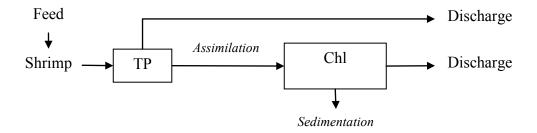
The N model (Figure 4.1) described the input of N from feed, production of ammonia through shrimp excretion, assimilation of ammonia by phytoplankton or nitrification, and loss of N through sedimentation, volatilization and discharge (Lorenzen *et al.*, 1997). Denitrification was excluded due to relatively low nitrate concentration compared to TAN. The N model had three state variables including TAN, NO, and phytoplankton-bound particulate N in the units of Chl. These three state variables represented the main N components in the water column (Lorenzen *et al.*, 1997).

Figure 4.1 Conceptual model of N input, transformation and removal in shrimp ponds. TN: total N; TAN: total ammonia N; NO: nitrate + nitrite; Chl: particulate N (modified from Lorenzen *et al.,* 1997).

The P model (Figure 4.2) described the input of P through shrimp feeding and excretion, assimilation of dissolved P by phytoplankton, and loss of P through sedimentation and discharge. P is less complicated than N in the cycling of inorganic

forms in water. Also, P is not generally the limiting nutrient in marine ecosystems, so just TP loading usually matters. To keep the P model simple but also informative, it only included two state variables, TP and phytoplankton-bound particulate P in the units of Chl.

Figure 4.2 Conceptual model of P input, transformation and removal in shrimp ponds. TP: total P; Chl: particulate P.

Mathematical models for N and P dynamics were formulated based on mass balance and nutrient fates. The model for N was taken from Lorenzen et al. (1997) and P model was newly included. Models were expressed by the following set of differential equations:

$$\frac{dC_{TAN}}{dt} = qA_N - [(n + v + f)C_{TAN} + gcC_{Chl}\frac{C_{TAN}}{C_{TAN}+C_{NO}}] \tag{1}$$

$$\frac{dC_{NO}}{dt} = nC_{TAN} - fC_{NO} - gcC_{Chl}\frac{C_{NO}}{C_{TAN}+C_{NO}} \tag{2}$$

$$\frac{dC_{TP}}{dt} = A_P - [fC_{TP} + sguC_{Chl}] \tag{3}$$

$$\frac{dC_{Chl}}{dt} = gC_{Chl} - (s + f)C_{Chl} \tag{4}$$

where q was proportion of N entering as TAN; A_N was total N input per day (mg l^{-1} day^{-1}); A_P was total P input per day (mg l^{-1} day^{-1}); C_{TAN} was the concentration of total ammonia nitrogen (mg l^{-1}); C_{NO} represented combined concentration of nitrate and nitrite

nitrogen (mg l^{-1}); C_{Chl} was the concentration of chlorophyll a (mg l^{-1}); c denoted nitrogen-to-chlorophyll ratio of algae; u represented phosphorous-to-chlorophyll ratio of algae; f was daily water exchange rate (% day^{-1}); g was growth rate of algae (% day^{-1}); n represented nitrification rate (% day^{-1}); s was sinking rate of dead algae (% day^{-1}); v denoted volatilization rate of ammonia (% day^{-1}); and t was time (days).

The total N and P waste were assumed proportional to shrimp metabolism (Lorenzen *et al.*, 1997):

$$A_N = a_N N_t W_t{}^{b_N} \tag{5}$$

$$A_P = a_P N_t W_t{}^{b_P} \tag{6}$$

where a_N and a_P were N and P waste produced by shrimp per unit weight per day (mg l^{-1} day^{-1}), respectively; b_N and b_P denoted allometric scaling factors of N and P metabolic rates; N_t represented shrimp population density; and W_t denoted mean body weight of shrimp (g).

Population density of shrimp N_t at time t was:

$$N_t = N_0 \exp(-Mt) \tag{7}$$

where M denoted instantaneous mortality rate of shrimp (day^{-1}); N_0 was stocking density (PL l^{-1}).

Shrimp mean body weight W_t at time t was given by a weight-based von Bertalanffy growth function (VBGF) (Gulland, 1983; Lorenzen *et al.*, 1997):

$$W_t = [W_\infty^{1/3} - (W_\infty^{1/3} - W_0^{1/3})\exp(-K_a t)]^3 \tag{8}$$

where K_a was the VBGF daily growth rate (% day^{-1}); W_0 denoted VBGF body weight at time of stocking (g); and W_∞ represented asymptotic VBGF body weight (g).

The growth rate of algae was denoted as g (Lorenzen *et al.*, 1997):

$$g = g_{max}L_{light}L_NL_P \tag{9}$$

where g_{max} was the maximum growth rate in the absence of limitation (% day^{-1}); L_{Light} was the light limitation coefficient; L_N was the nitrogen limitation coefficient; and L_P was the phosphorus limitation coefficient.

The light limitation coefficient was defined by Lambert-Beer Law (Steele, 1962; Lorenzen *et al.*, 1997):

$$L_{light} = \frac{e}{k}\left\{\exp\left[-\frac{I_0}{I_{sat}}\exp(-kz)\right] - \exp\left(-\frac{I_0}{I_{sat}}\right)\right\} \tag{10}$$

where e was the base of the natural logarithm; $I_{ratio}(= I_0/I_{sat})$ was the ratio of the surface light intensity to the saturation light intensity (Burford and Lorenzen, 2004); k denoted the extinction coefficient (m^{-1}); and z was water depth (m).

The extinction coefficient k was (Lorenzen *et al.*, 1997):

$$k = k_{chl}C_{chl} + k_{other} \tag{11}$$

where k_{Chl} represented extinction per unit concentration of chlorophyll (m^{-1} mg^{-1}); and k_{other} denoted extinction due to non-chlorophyll sources (m^{-1}).

N and P limitation were defined as (Lorenzen *et al.*, 1997):

$$L_N = \frac{C_{TAN}+C_{NO}}{(C_{TAN}+C_{NO})+K_{S_N}} \tag{12}$$

$$L_\mathrm{P} = \frac{C_\mathrm{DRP}}{C_\mathrm{DRP}+K_{S_\mathrm{P}}} \tag{13}$$

where C_DRP represented the concentration of dissolved reactive P (mg l^{-1}); Ks_N was the half-saturation constant of N (mg l^{-1}); and Ks_P was the half-saturation constant of P (mg l^{-1}).

Nitrification, volatilization, sedimentation and discharge of nutrients were considered as first-order rate processes (Lorenzen *et al.*, 1997). The models were implemented in MATLAB (R2011b version, The MathWorks, Inc) using IDEAS toolbox. IDEAS (IDEntification and Analysis of Sensitivity) can automatically estimate parameters of ordinary differential equations (ODEs) and assess their uncertainty (Munoz-Tamayo *et al.*, 2009).

Models were calibrated using my observed data. Following Lorenzen et al. (1997) and Burford and Lorenzen (2004), management parameters were derived from field data directly 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). The IDEAS toolbox was used to compute the first-order sensitivity coefficients of the four state variables with respect to the dynamic parameters. Correlation of estimated parameters was also examined.

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.

Results

Model calibration

To determine VBGF growth parameters, shrimp growth curve was approximated using the weight-based von Bertalanffy growth function (Figure 4.3). Observed mean body weight of shrimp was 0.05 g at stocking and reached 18 g at harvest. With an

exponential increase, estimated VGBF weight of shrimp at stocking (W_0) was 0.08 g and VGBF maximum weight of shrimp (W_∞) was 72 g. Actually, shrimp only reached VGBF weight of 16.7 g at harvest after 100 d, so they would never reach W_∞ in culture.
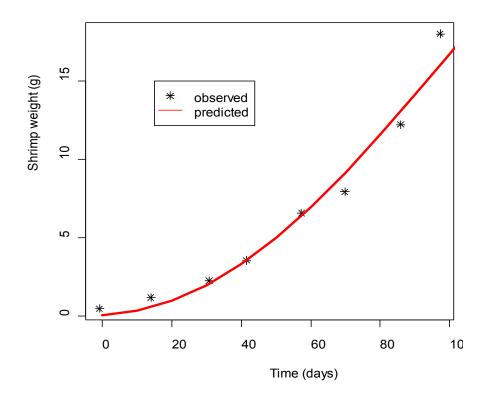
Figure 4.3 Predicted weight of shrimp at time t using von Bertalanffy growth function.
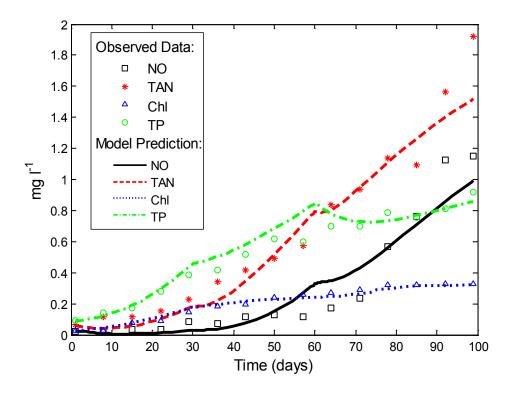
Most management and environment parameters were determined from field data and fixed (Table 4.1). Parameters to be estimated included s, n, v, g_{max}, I_{ratio}, k_{SN}, k_{SP}, c, u, b_P. The N and P dynamic models were optimized to extract a combination of 10 nutrient dynamics parameters that provided best fit to the observed data of TAN, NO, TP and Chl (Table 4.1).

Table 4.1 Model parameters.

Model parameters	Values	Reference
Management/environment parameters (fixed)		
K_a (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	

The calibrated models were run for the whole production cycle and simulated values were plotted against the observed values (Figure 4.4). 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.
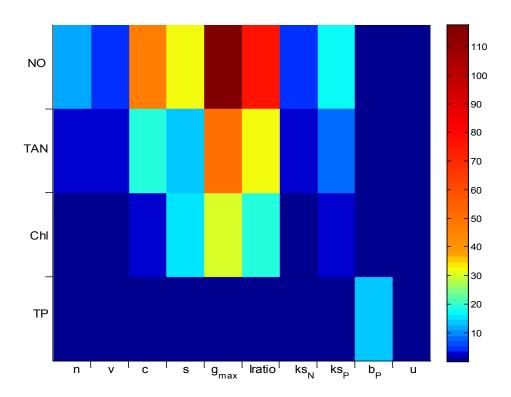
Figure 4.4 Model predictions and mean observed values of TAN (total ammonia nitrogen), NO (nitrite + nitrate), Chl (chlorophyll) and TP (total phosphorus) over a production cycle.

Sensitivity analysis

Sensitivity analysis was performed to identify parameters which had strong effects over different state variables. A heat map was created to visualize the sensitivity of model outputs with respect to the estimated parameters (Figure 4.5). High values (at

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the dark red end) indicated high sensitivity, while low values (at the dark blue end) represented less sensitivity. TAN, NO and Chl were strongly affected by the growth of phytoplankton (g_{max}), light intensity ratio (I_{ratio}), algae sinking rate (s) and nitrogen-to-chlorophyll (c). TP concentrations were only sensitive to allometric scaling of TP input (b_P). Estimated parameters in the models also showed some correlation, with 7 pairs of variables highly correlated (Table 4.2).
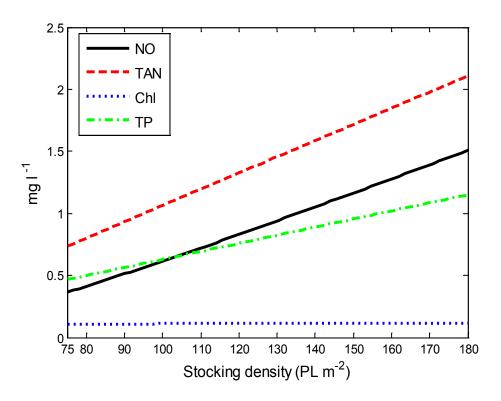
Figure 4.5 Sensitivities of model outputs with respect to the estimated parameters. TAN: total ammonia nitrogen; NO: nitrite + nitrate; Chl: chlorophyll; TP: total phosphorus.

Table 4.2 Correlation matrix for the estimated parameters in the models, with significant correlations indicated by bold numbers.

	n	v	c	s	g_{max}	I_{ratio}	k_{SN}	k_{SP}	bp	u
n	1.00									
v	**-0.88**	1								
c	0.19	-0.19	1							
s	-0.08	0.07	**-0.99**	1						
g_{max}	0.66	-0.71	0.73	-0.65	1					
I_{ratio}	-0.66	0.71	-0.73	0.65	**-1.0**	1				
k_{SN}	0.64	-0.69	0.53	-0.44	0.8	**-0.84**	1			
k_{SP}	-0.29	0.32	-0.44	0.40	-0.5	0.55	**-0.88**	1		
bp	0.15	-0.16	0.03	-0.01	0.1	-0.12	0.12	-0.06	1	
u	0.10	-0.10	**0.97**	**-0.97**	0.7	-0.65	0.45	-0.40	0.17	1

Impacts of management strategies
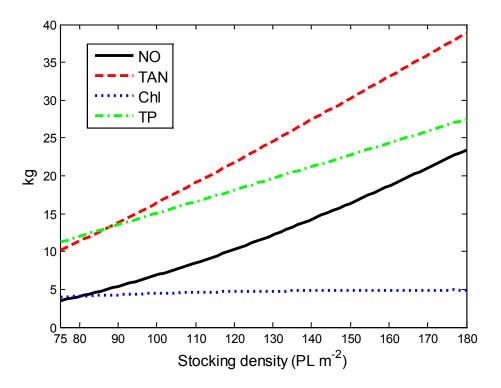
Predictions of the effect of stocking density on end-of-cycle concentrations of TAN, NO, TP, and Chl were simulated (Figure 4.6). Increasing stocking density increased the concentrations of TAN, NO and TP in the water column. TAN increased at a faster rate than NO and TP. For stocking density from 75-180 PL m^{-2}, end-of-cycle concentrations of TAN ranged from 0.75 to 2.1 mg l^{-1}, NO from 0.4 to 1.5 mg l^{-1}, and TP from 0.48 to 1.2 mg l^{-1}. Concentrations of Chl remained almost constant at 0.15 mg l^{-1} with respect to increasing stocking density.

Figure 4.6 Impact of stocking density on concentrations of TAN (total ammonia nitrogen), NO (nitrite + nitrate), Chl (chlorophyll) and TP (total phosphorus) at the end of the production cycle.
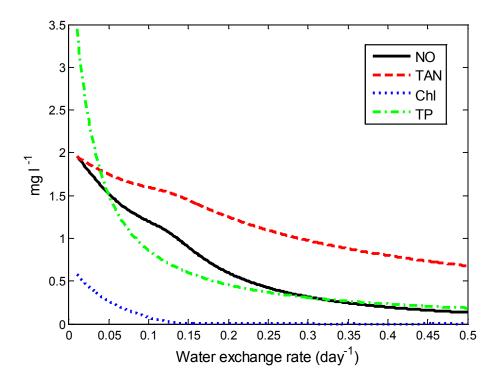
The effect of stocking density on loading of TAN, NO, TP, and Chl were simulated (Figure 4.7). Under the assumption of the same survival rate, shrimp production ranged from 5.4-13 tonnes ha^{-1} for stocking density from 75-180 PL m^{-2}. Increasing stocking density increased loading of TAN, NO and TP to the receiving waters. TAN increased at a faster rate than NO and TP. TAN loading ranged from about 10-40 kg each pond (30-120 kg ha^{-1}) per cycle, and estimated discharge of TAN was about 5.6-9 kg per tonne of shrimp produced. NO loading ranged from 4-24 kg each pond (12-72 kg ha^{-1}) per cycle, and estimated discharge of NO was about 2.2-5.6 kg per tonne of shrimp produced. P loading ranged from 11-28 kg each pond (33-84 kg ha^{-1}) per cycle, and estimated P discharge was about 6.1-6.5 kg per tonne of shrimp produced. Discharge

of Chl remained almost constant at 4 kg from the studied pond (12 kg ha^{-1}) per cycle regardless of increasing stocking density.

Figure 4.7 Impact of stocking density on loading of TAN (total ammonia nitrogen), NO (nitrite + nitrate), Chl (chlorophyll) and TP (total phosphorus) from one shrimp pond (pond size = 0.3 ha).
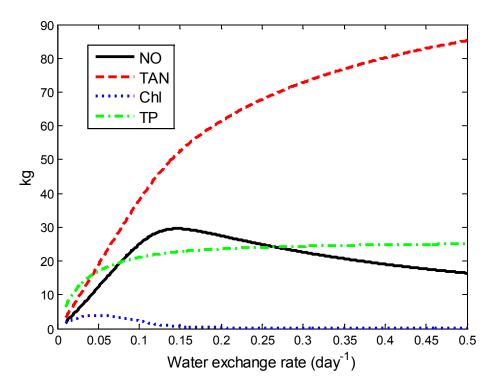
The effect of water exchange on end-of-cycle concentrations of TAN, NO, TP, and Chl were simulated (Figure 4.8). Increasing water exchange reduced the concentrations of TAN, NO, TP and Chl in the water column. For water change rates from 1-50% day[-1], end-of-cycle concentrations of TAN declined from 2 to 0.7 mg l^{-1}, NO from 1.9 to 0.15 mg l^{-1}, TP from 3.4 to 0.2 mg l^{-1} and Chl from 0.6 to 0 mg l^{-1}. There was a sharp decline of TP at exchange rate of 1-10% day[-1] and a steady decrease afterwards. Chl concentrations reached almost 0 mg l^{-1} when water exchange rate was above 15% day[-1].

Figure 4.8 Impact of water exchange on concentrations of TAN (total ammonia nitrogen), NO (nitrite + nitrate), Chl (chlorophyll) and TP (total phosphorus) at the end of the production cycle.

The effect of water exchange on loading of TAN, NO, TP, and Chl were also simulated (Figure 4.9). Shrimp production for each water management scenario was assumed to be the same at 9.5 tonne ha^{-1}. Increasing water exchange increased loading of TAN and TP to the receiving waters. TAN increased at a faster rate than TP. TAN loading ranged from about 2-85 kg each pond (6-255 kg ha^{-1}) per cycle, and estimated discharge of TAN was about 0.65-26 kg per tonne of shrimp produced. P loading ranged from 7-25 kg each pond (21-75 kg ha^{-1}) per cycle, and estimated P discharge was about 2.2-7.7 kg per tonne of shrimp produced. Loading of NO increased up to 30 kg per shrimp pond (90 kg ha^{-1}) for water exchange rate from 1-15% per day, but then declined to 17 kg per pond (51 kg ha^{-1}) afterwards. Highest discharge of NO was 9.3 kg per tonne
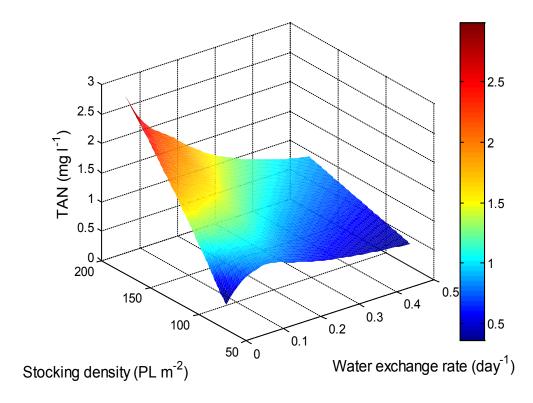
of shrimp produced with 15% of daily water exchange. Loading of Chl increased up to 3 kg per shrimp pond (9 kg ha^{-1}) for water exchange rate from 1-5% per day, but then declined to 0 at 15% of daily water exchange or above.
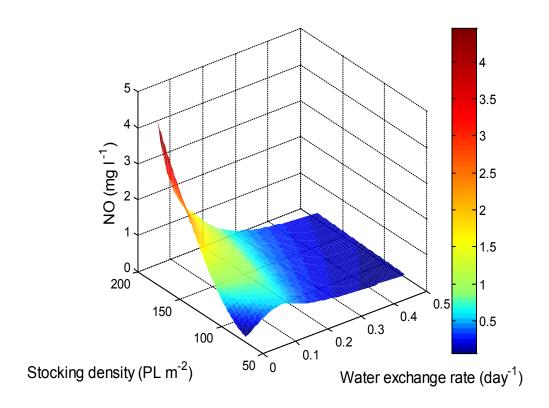
Figure 4.9 Impact of water exchange on loading of TAN (total ammonia nitrogen), NO (nitrite + nitrate), Chl (chlorophyll) and TP (total phosphorus) from one shrimp pond (pond size = 0.3 ha).

The combined effects of stocking density and water management on end-of-cycle concentrations of TAN, NO, TP, and Chl were simulated (Figure 4.10-4.13). 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
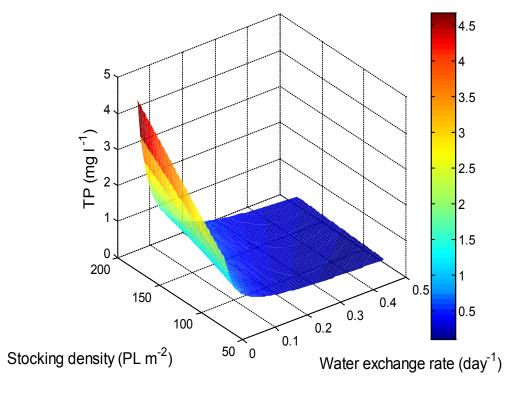
water exchange, regardless of the stocking density. Lowest concentration of Chl was achieved at highest water exchange rate.
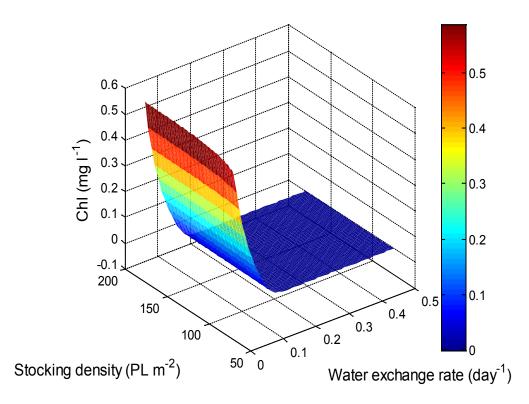
Figure 4.10 The combined effects of stocking density and water exchange on concentrations of TAN (total ammonia nitrogen) at the end of the production cycle.

Figure 4.11 The combined effects of stocking density and water exchange on concentrations of NO (nitrite + nitrate) at the end of the production cycle.
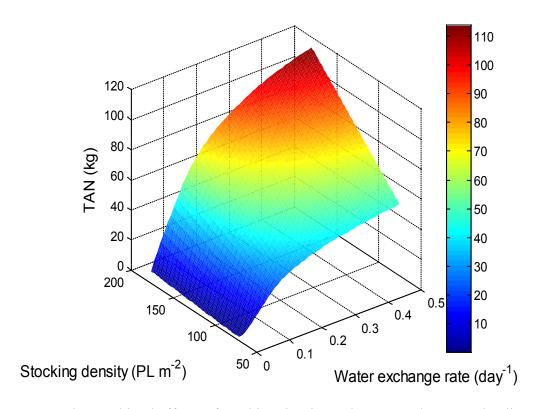
Figure 4.12 The combined effects of stocking density and water exchange on concentrations of TP (total phosphorus) at the end of the production cycle.
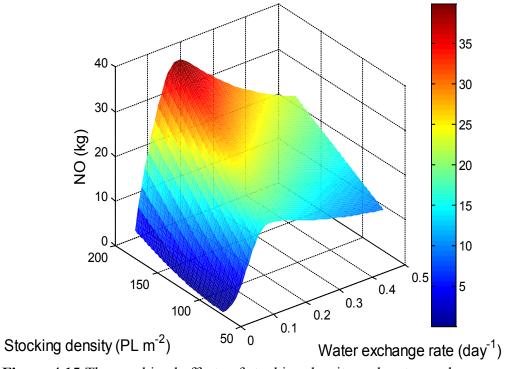
Figure 4.13 The combined effects of stocking density and water exchange on concentrations of Chl (chlorophyll) at the end of the production cycle.
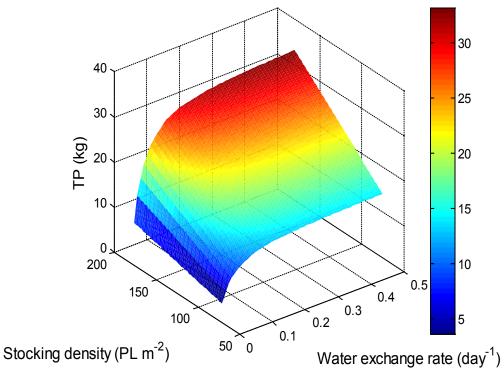
The combined effects of stocking density and water management on nutrient loading from one shrimp pond (pond size = 0.3 ha) were also simulated (Figure 4.14-4.17). At lower water exchange rate up to 20% per day, loading of NO was less than 10 kg from the pond (< 30 kg ha^{-1}). NO discharge reached maximum 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.
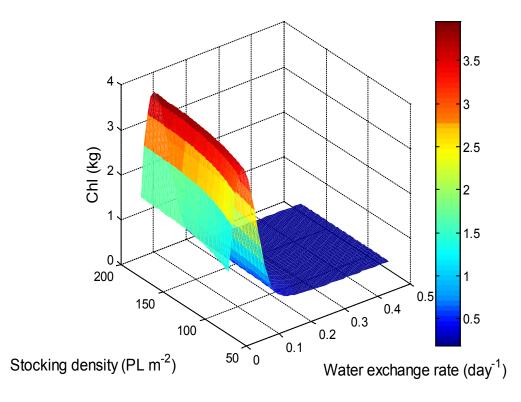
Figure 4.14 The combined effects of stocking density and water exchange on loading of TAN (total ammonia nitrogen) from one shrimp pond (pond size = 0.3 ha).

Figure 4.15 The combined effects of stocking density and water exchange on loading of NO (nitrite + nitrate) from one shrimp pond (pond size = 0.3 ha).

Figure 4.16 The combined effects of stocking density and water exchange on loading of TP (total phosphorus) from one shrimp pond (pond size = 0.3 ha).

Figure 4.17 The combined effects of stocking density and water exchange on loading of Chl (chlorophyll) from one shrimp pond (pond size = 0.3 ha).

Discussion

The models

The 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 pioneer studies (Lorenzen *et al.*, 1997; Burford and Lorenzen, 2004; see Table A14 in Appendix). 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 my results.

Following Lorenzen et al. (1997) and Burford and Lorenzen (2004), commercial feed was assumed as the exclusive contributor for both N and P in my models. Many previous studies have shown that about 90-95% of the N and P inputs to intensive shrimp ponds come from the formulated feed, while only a small proportion (5-10%) comes from water inflow, shrimp stock, and other inputs such as leaching from sediment (Lorenzen *et al.*, 1997; Funge-Smith and Briggs, 1998; Jackson *et al.*, 2003; Burford and Lorenzen, 2004). Although this assumption might lead me to slightly underestimate the actual nutrient inputs, it did not significantly affect accuracy of the results.

In this study, shrimp ponds were completely drained and no sludge was collected at the end. Thus my models excluded sludge remineralization. Few studies considered the dynamics of nutrient accumulation in the sludge and incorporated sludge remineralization (Burford and Lorenzen, 2004). This is probably due to difficulties in accurate measuring volume of sludge and complicated roles of sludge N components. Lorenzen et al. (1997) excluded sludge remineralization in their study as well. Burford and Lorenzen (2004) incorporated sludge remineralization in their models but found it made little contribution to the evaluation of management strategies.

There are very few studies of P dynamics in marine shrimp ponds. This was probably because P was not the key limiting nutrient in marine ecosystems. Only Montoya et al. (2000) evaluated the impacts of feed formulations and feeding strategies on P dynamics. Incorporation of P dynamics in the present study permitted the analysis of dynamic interaction of P input, algae assimilation, sedimentation and effluent discharge over a production cycle. Different management strategies could also affect the rates of nutrient cycling (Burford and Lorenzen, 2004). Thus it was difficult to compare estimated P parameters in the present study to other values in order to evaluate relative accuracy.

The models were calibrated to estimate a combination set of 10 parameters from a small and heterogeneous dataset. Models were optimized using a maximum likelihood approach and best-fitting set of parameters were extracted when local optimum was achieved. However, parameter estimation was performed over a certain range and results were sensitive to the initial values which made this modeling method somewhat subjective. Different initial values of parameters would return slightly different best-fitting sets of parameters. Through sensitivity analysis, some estimated parameters were

found to be highly correlated. True correlation probably does exist between some physically or ecologically linked paramteters. For example, magnitude of N volatilization (v) determines loss of N and thus availability of N for nitrification (n). I_{ratio} indicates the light limitation, which is negatively correlated with algae growth (g_{max}). But some uncorrelated parameters may also show high correlation that is not really functional, such as algae sinking rate (s) and phosphorus-to-Chl ratio (u). The reason might be that data were insufficient to separate the effects of individual parameters on nutrient dynamics in the models (Lorenzen $et\ al.$, 1997). However, the identified set of paramters was consistent with the available information. Although the models had some limitations, 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.

Nutrients

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 tonne of shrimp

produced for the model shrimp system were 72 and 18 kg, 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. My 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 tonne of shrimp produced in semi-intensive shrimp ponds were 73.3 and 13.2 kg, respectively (Casillas-Hernández *et al.*, 2006). My results of nutrient losses per tonne of shrimp produced were comparable with those of semi-intensive systems due to high unit production in the intensive ponds.

At the end of production cycle, observed concentrations of TAN, NO, and TP were about 1.9 mg l^{-1}, 1.2 mg l^{-1} and 0.9 mg l^{-1}, respectively. All values were higher than those reported for some intensive shrimp farms (Burford and Lorenzen, 2004; Xia *et al.*, 2004). This was probably due to higher farm intensity in this study. The TAN and TP concentrations allowed by effluent standards were 5 mg l^{-1} or less and 0.5 mg l^{-1} or less, respectively (Boyd, 2003). TAN levels were always below this limit, but TP levels were higher than the standard from day 30 on. Dissolved inorganic nitrogen and phosphorus would be assimilated by algae, which are the primary pathway of N and P removal (Jimenez-Montealegre *et al.*, 2002). However, nutrient assimilation by algae would be limited by nutrient concentrations, light limitation, and algal self-shading (Lorenzen *et*

al., 1997; Jimenez-Montealegre *et al.*, 2002). The total phytoplankton biomass was measured as Chlorophyll a concentration. Observed concentrations of Chl showed a major increase from 0.025-0.38 mg l^{-1} over the production cycle, which indicated algae assimilation was one of the key processes in nutrient dynamics.

Impacts of management

Stocking density is often considered to have a major influence on water quality (Burford and Lorenzen, 2004). Current intensive shrimp farming in China could be further divided into intensive and super intensive, with wide variation in stocking densities from 75-180 PL m^{-2}. Nutrient levels in the water column increased with intensification of the shrimp farming system. Phytoplankton production showed little increase and remained almost constant with increasing stocking density. This indicated that primary production in the pond was limited by nutrients, light, or self-shading at higher stocking density, and algae assimilation capacity was achieved. Since N and P inputs already exceeded the assimilation capacity of phytoplankton, excessive N and P resulted in high concentrations of TAN, NO and TP in the water column. The shrimp ponds studied could not rely on natural methods for nutrient removal so and other treatment techniques were needed. Stocking density also had significant impact on nutrient loading. Nutrient loading to the receiving waters increased with the intensification of the shrimp farming system. Higher unit production resulted in relatively more nutrient loading due to higher feed consumption. Super-intensive systems could contribute more nutrient loading than regular intensive systems. Using relatively low stocking density for intensive farming systems can reduce nutrient loading to receiving

waters. Nutrient loading to the receiving waters is not always harmful, as it depends on the self-purification capacity of the receiving waters.

How to effectively manage water exchange at the farm level to abate environmental impacts of shrimp farming is controversial (Lorenzen *et al.*, 1997). Farmers tended to exchange water at high daily rates to maintain water quality at satisfactory levels for the crop. However, discharge of untreated effluents with high nutrients and organic matter deteriorates water quality in the receiving waters. Some studies support low or zero water exchange to minimize the risk of water contamination and cross-farm pollution by pathogens from other disease-affected farms (Lorenzen *et al.*, 1997). In my study, model results suggested that water exchange at 15% daily could completely eliminate Chl, because high water exchange effectively diluted Chl at a faster rate than the growth of algae (Lorenzen *et al.*, 1997; Burford and Lorenzen, 2004). But there was little benefit for high water exchange rate to remove Chl, which would indirectly limit the assimilation of nutrients by phytoplankton. I also found that increasing water exchange increased loading of TAN and TP to receiving waters. Water exchange could partly remove NO from shrimp ponds. To keep TP levels under the limit of 0.5 mg l^{-1}, at least 15% of daily water exchange rate should be implemented. This indicated that water exchange was insufficient and other water treatment strategies should be adopted. Bio-filter and bio-floc technologies can be efficient methods to remove nutrients and maintain water quality in aquaculture systems (Crab *et al.*, 2007). If these nutrient removal techniques were adopted, water exchange could be minimized, which could result in a cost savings to farms and reduced eutrophication potential from pond effluents.

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). My 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 my 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

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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 tonne of shrimp produced for the model shrimp system were 72 and 18 kg, 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.

Conclusion

This study was the first approach to evaluate the impacts of management strategies on both N and P dynamics over a complete production cycle. A combination of moderate stocking density and reduced water exchange rate would probably be the most optimistic scenario that could achieve a win-win situation with low nutrient loading while maintaining high shrimp production. Future research should continue and concentrate on optimizing shrimp farming system to minimize environmental impacts and maintain/improve farm production towards a more sustainable future of the shrimp farming industry.

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CHAPTER 5

CHARACTERIZATION OF CHINESE SHRIMP FARMING SYSTEMS TOWARDS TYPOLOGY, ECONOMIC AND SOCIAL SUSTAINABILITY

Introduction

As one of the most important seafood industries, world shrimp farming has undergone an exponential expanding over the last few decades. Increase in shrimp production has been achieved by system intensification to help meet growing demand from export markets. Global production of farmed shrimp has increased from less than 9000 tonnes in 1970 to about 3.2 million tonnes in 2008, which ranked second in world aquaculture production in value and fourth in quantity compared to other fish species (Cao *et al.*, 2011). China and Thailand are leading producers, and contribute 80% of the global production (Biao and Kaijin, 2007). The shrimp farming industry has played an important role in the economy of China since 1990s, as development of shrimp farming generated significant income, employment and export earnings (Biao and Kaijin, 2007).

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 conceptually 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 effective 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 categorize 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 compose of 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 cost the shrimp industry billions of dollars in lost crops, jobs and export revenue, which almost led to collapse of the shrimp industry in the 1990s in many Asian countries (Lightner, 2005; 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 tonnes 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.

I have already evaluated environmental sustainability of Chinese shrimp farming systems (Cao *et al.*, 2011). This paper extended the purpose and focused on examining economic sustainability of shrimp production in China. The objectives of the study were: 1) evaluate the diversity of shrimp farms towards its typology using multivariate techniques, 2) compare the identified farming systems for their technical characteristics and financial performance to determine the most profitable system, 3) assess key management practices that had significant impacts on farm profitability, 4) modeling risk of disease outbreak on farm economy, 5) investigate potential of implementing effluent treatment and participating certification programs by shrimp farmers, 6) evaluate changes in quality of life of farmers . My results can provide practical insights for decision- or policy-making in order to promote good management practices towards economic and social sustainability.

Methods

Data collection

Data for this study 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 and feed use; farming techniques such as stocking density and aeration rate; production costs; disease outbreak; as well as main problems during shrimp culture. Local shrimp farmers identified 4 main farming types based on their conceptual classification: intensive small-scale, intensive commercial-

scale, semi-intensive, and polyculture farms. I randomly selected 25 farms for each type. A total of 100 shrimp farms differed in level of intensity, diversity, and labor origin were 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 cost (Michielsens *et al.*, 2002).

Classification of farming types

In order to be certain about the types of shrimp farms, I studied typology of shrimp farming based on empirical classification by employing multivariate techniques and compared my results with farmers' conceptual classification. 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.

Since most of the variables were correlated, factor analysis was first employed to create a smaller set of composite variables (Joffre and Bosma, 2009). 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. Kaiser-Meyer-Olkin (KMO) was an index used to examine the appropriateness of applying factor analysis to the data set. Bartlett's test was conducted to examine the hypothesis that variables are uncorrelated.

After factor analysis, shrimp farms were clustered according to the new factors. First, both a hierarchical (Ward's method) and a non-hierarchical (partitioning around medoids, PAM) cluster technique 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 method 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 (tonnes ha^{-1} yr^{-1}) and profits (RMB ha^{-1} yr^{-1}) as functions of management variables using the backward selection method. Independent variables were entered with probability smaller than 0.10. Management variables included farm size (ha), stocking density (PL m^{-2}), daily water exchange rate, aeration rate (hrs ha^{-1} yr^{-1}), feeding rate (tonnes ha^{-1} yr^{-1}).

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 percentage of shrimp loss affected 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. 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

Classification and characterization

Variables were correlated and data collected in this study were appropriate for a factor analysis, with KMO (Kaiser-Meyer-Olkin) of 0.838 (> 0.7, 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 5.1). Most of the uniquenesses were smaller than 0.5 and close to 0, which suggested the model fit well. I started by retaining and highlighting variables with loadings larger than 0.5 in absolute value to be the main components of each factor.

Table 5.1 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 (tonnes 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	.1270	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	
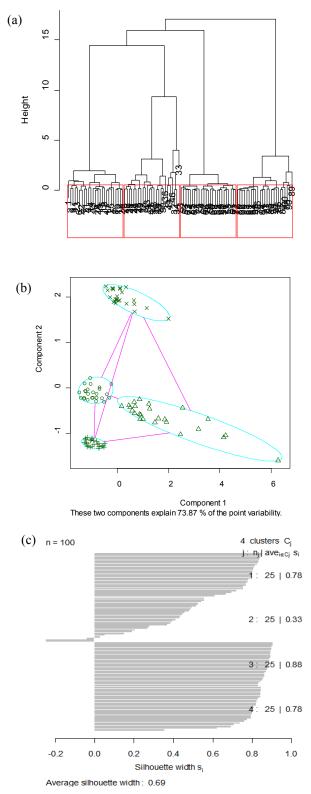
Notes: *PL= post larvae; #1 RMB = 0.15 USD.

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 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 47.8% of the total variance.

Factor 2 was composed of two groups of 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 5.1).

Figure 5.1 (a) Hierarchical clustering dendrogram with red borders based on Ward's method for estimating numbers of clusters; (b) Cluster plot of 4-cluster solution based on non-hierarchical PAM method; (c) Silhouette plot of 4-cluster solution based on non-hierarchical PAM method.

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. 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 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 had been found.

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 5.2. 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 (cluster 1) and commercial farms (cluster 2) shared many similar characteristics. They both operated significantly smaller ponds with significantly higher stocking densities compared to semi-intensive (cluster 3) and polyculture (cluster 4) farms ($P < 0.05$). Both intensive farming systems produced shrimp yearly around with a total of three crops and duration of 90-120 days per crop. They had significantly higher frequencies of water exchange 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 semi-intensive and polyculture ($P < 0.05$). Intensive family had the

highest start-up investment 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 only differed in labor origin and farm size. Intensive family farms were all 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.

Table 5.2 Technical characteristics of Chinese shrimp farming systems identified by cluster analysis.

Parameters	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 (tonne 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

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

Semi-intensive (cluster 3) and polyculture (cluster 4) 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 was monoculture system with lower stocking density and less intensification than 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 in 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 investment 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 5.3). Seed and electricity were another two highest input costs in both intensive farming systems. Fertilizers and seed were also considered as main inputs in the semi-intensive farming system. Of fixed costs, land lease was the major input cost in all farming systems.

Table 5.3 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%**

Economic performance

Shrimp yields, production costs, profits, survival rates, as well as resource (feed, capital and labor) use efficiency were computed for the four shrimp farming systems

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(Table 5.4). 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 level of profit. By obtaining extra profits 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.

Table 5.4 Comparison of economic performance and resource use efficiency of shrimp farming systems.

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 (tonnes 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 (tonnes 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})	$191,000 \pm 1,9000^{a}$	$183,000 \pm 17,000^{a}$	$72,600 \pm 6,300^{c}$	$99,700 \pm 7,400^{b,*}$
Profit (RMB ha^{-1} crop^{-1})	$63,600 \pm 6,500^{a}$	$61,000 \pm 5,600^{a}$	$36,300 \pm 3,100^{c}$	$47,300 \pm 7,500^{b,*}$
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}	$120.8 \pm 30.7^{a,*}$

Notes: 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.

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 5.5 and 5.6). These predictor variables included stocking density, feeding rate and aeration rate, which had significant effects on yields and net profits and were considered as influential factors. Two other independent variables, farm size and water exchange rate, showed insignificant impacts on the two response variables and thus were excluded by the models. All three influential factors were positively correlated with yields and net profits.

Table 5.5 Influential factors of net profits and their coefficients based on multiple linear regression modeling (constant = 31,900; adjusted $R^2 = 0.932$).
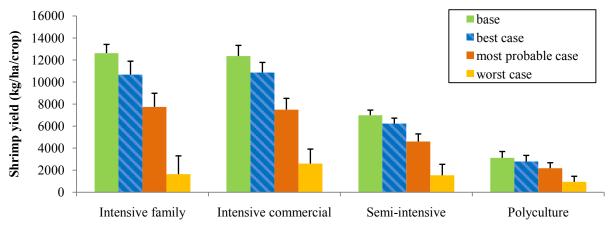
Predictors	Unstandardized coefficient ± Std. error	Standardized coefficient	*P*-value
Aeration rate (hrs ha^{-1} yr^{-1})	0.878 ± 0.152	0.435	<0.05
Feeding rate (tonnes ha^{-1} yr^{-1})	$1,600 \pm 178$	0.473	<0.05
Stocking density (PL m^{-2})	154 ± 58.4	0.13	<0.05

Table 5.6 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 (tonnes ha^{-1} yr^{-1})	.175 ± 0.028	.197	<0.05
Stocking density (PL m^{-2})	.192 ± 0.009	.615	<0.05

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 for the three scenarios including worst, best, and most probable case were estimated for each farm based on its own estimation of disease occurrence rates. Modeled yields were compared with base yields (Figure 5.2). I assumed yields obtained during the survey were disease-free base yields. Disease outbreak showed highest influence on intensive farming, especially on intensive family farms. Polyculture farms were least affected by disease occurrence.

Figure 5.2 Effects of disease outbreak on shrimp yield given different disease levels (Mean + S.D.).

Perceptions of changes in quality of life

All respondents agreed that shrimp farming had significantly positive impacts on the development of 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) in general the environment in the village is better than in the past such as more roads were built; 3) more education opportunity for children now; 4) less crime in the village; 5) less illness than in the past and people who get sick have more chance to access medical service now; 6) villages have grown in the last 10 years. However, farmers also consented that more water and soil pollution were caused by shrimp farming in the region.

Discussion

Current 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 in southern China usually culture two to three crops per year, while only one to two crops in northern China (Biao and Kaijin, 2007). The majority of extensive managed shrimp farms have been replaced by more intensified farming types. For my analysis, I sampled 100 shrimp farms from the concentrated shrimp farming regions in Hainan province. Total area of my sampled farms was 715 hectares, representing 8.5% of shrimp farming areas 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, I was able to visit a few large commercial farms wearing

special uniforms after strict sterization procedures, and successfully incorporated them into my 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), I employed similar variables which reflected the operating characteristics, diversity and labor origin of shrimp farms. I 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), I 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. My classification results were consistent with information of farm types 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 their long-term sustainability could still be questionable due to disease outbreak. Future research is needed to improve intensive systems to achieve long-term economic sustainability. My study found survival rates were relatively higher in semi-intensive ponds than intensive ponds due to lower stocking density and better water quality in the later ponds. High survival rates of shrimp could also be achieved in small intensive ponds under best 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 the 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 minimized. However, polyculture farms did not prevent farms from virus infections and farms were still vulnerable to disease if inappropriately managed. In my study, polyculture farms integrated shrimp and tilapia with ratios of 10:1 (30 PL per m^2 and 3 fish per m^2 at 10 g) or 15:1 (45 PL per m^2 and 3 fish per m^2 at 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

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or nursing them in separate ponds, and found farmers' year of experience and harvest methods also had significant impacts on net profits. I found farm size and water exchange rate had insignificant effect on farm profits. Pond size was shown to be important in explaining the profitability of shrimp farms by Gordon and his colleague (Gordon and Bjørndal, 2009). Small production units could 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 early start of aeration resulted in higher survival rates. Raising aeration from 9,000 to 14,000 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 my 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, which were more disease resistant and grew faster than local strains (Lightner, 2005). A shift from black shrimp to SPF white shrimp enabled producers 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). My results indicated that disease outbreak could cause only 12% to 36% crop failure at the best or probable cases, and as much as 78% crop failure at the worst case. Disease risk usually depends on the causes of disease, such as bacteria or virus based, time of disease occurrence and shrimp size at that time, as well as 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 my 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 my 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).

Potential negative impacts of effluents from shrimp farming include eutrophication of receiving waters, contamination of waters with virus and bacteria, as well as biodiversity degradation. The extent of impacts depend on farm intensity and the carrying capasity of receiving water bodies. Effluents from intensive farming tend to have the highest negative impacts on the environment (Boyd, 2003). Untreated effluents might exacerbate water quality and spread disease to nearby farms, which would eventually increase the risk of crop failure and harm farm profitability. To promote more sustainable production, shrimp farms, especially intensive farms, should establish and operate effluent treatment to minimize the risk of water pollution. There are many technologies including physical, chemical and biological available for effluent treatment (Boyd, 2003; Cao *et al.*, 2007). The majority of farms (86%) in my 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 my survey were reluctant to invest money on effluent treatment and would only be willing to implementing effluent treatment under financial subsidies or mandatory requirement by the government. Governmental subsidies would be a positive approach to ensure smallholders implementing effluent treatment. Crab *et al*. (2007) calculated costs per kg of fish produced per year for different biofilters used for water treatment. Fluidized sand biofilters and bead biofilters were the least expensive options, costing US$0.27 and

US$0.67 per kg of fish per year respectively (Crab *et al.*, 2007). Government could use these values to determine reasonable amount of subsidies to small-scale shrimp farmers.

Given the high tradability of shrimp, trade policy can be another consideration 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 main problem 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 my 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 noticed 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.

Shrimp farming showed some negative impacts on the community such as confliction in land and water use (Clarke, 2003). These impacts were not detected in this study in Southern China. Although this study didn't establish a causal link between shrimp aquaculture and community development, it investigated some indicators of changes in quality of life from the perspective of shrimp farmers and other villagers. Improvements include more paved roads and employment opportunities, higher household income, and easier medical access. In general, people lived a happier life and considered their quality of life was improved by shrimp farming in the region.

Conclusion

Shrimp farming will continue to expand and play an important role in the economy of China. Shrimp farming systems will also continue to be intensified due to the stimulus of great economic returns. Disease outbreak caused by system intensification will consequently become the main constraint to sustainable development of the sector. A production system which is both economically profitable and environmentally sustainable is highly desired. Future studies are needed to discover ways to achieve this win-win situation and realize truly sustainable shrimp production.

Quantitative identification and characterization based on factor and cluster techniques were useful to understand farm diversity and identify farm typology. Four farming systems were identified in my study and their economic performance were compared. Intensive family and commercial farms showed the highest profitability, followed by polyculture and semi-intensive farms. Management strategies including stocking density, aeration rate and feeding rate had significant influence on farm profitability. Farm size and water exchange rate showed insignificant impacts on farm economics. Disease outbreak had the largest influence on intensive family and commercial farms, and least influence on polyculture farms. My results could assist decision makers developing more specific policies for each targeted farming type, which would lead to improved management practices for more profitable production. Adopting good management practices such as implementing effluent treatment in shrimp farming and participating in certification programs should be promoted, but challenges will exist, particularly for small- or medium-scale, family-operated farms. Further studies are needed to evaluate potential incentives for implementing good management practices such as financial aid or subsidy from the government.

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CHAPTER 6

CONCLUSIONS

Shrimp farming will continue to expand and play an important role in the economy of China. Shrimp farming systems will also continue to be intensified due to the stimulus of economic returns. Disease outbreak caused by system intensification will consequently become the main constraint to sustainable development of the sector. A production system which is both economically profitable and environmentally sustainable is highly desired.

This dissertation is the first approach to develop a comprehensive framework for evaluating and enhancing the sustainability of the shrimp farming industry. The quantifiable benefits include direct evaluation of shrimp farming systems to advise regulation and environmental impact mitigation measures for policy makers, to guide shrimp farmers toward implementing good aquaculture practices, and to inform consumers in their awareness and choice for more sustainable consumption.

LCA is an appropriate means and will become a mainstream tool to evaluate global and local environmental impacts of seafood production systems. As a systematic approach, LCA can evaluate sustainability of aquaculture systems quantitatively from a cradle-to-end perspective. By assessing system performance, it presents a useful basis for system improvement in terms of environmental sustainability and development of certification or eco-labeling criteria. However, existing LCA methods are not capable of

quantifying local ecological and socio-economic impacts, which limits its ability and future application. More efforts should be given to adapt the tool to aquaculture applications, as well as integration of current missing (such as biodiversity and risk of disease) or immature (such as socio-economic) impact categories for more comprehensive evaluations of system or product sustainability. Overall, LCA has great potential in assisting decision making for more sustainable seafood production and consumption.

Intensive farming had significant higher environmental impacts per unit production than semi-intensive farming in all impact categories. The grow-out stage contributed the highest impacts overall. These impacts were mainly caused by feed production, electricity use and farm-level effluents. By averaging over intensive (15%) and semi-intensive (85%) farming systems, 1 tonne live-weight of shrimp production in China required 38.3 ± 4.3 GJ of energy, as well as 40.4 ± 1.7 tonnes of net primary productivity, and generated 23.1 ± 2.6 kg of SO_2 eq, 36.9 ± 4.3 kg of PO_4 eq, and 3.1 ± 0.4 tonnes of CO_2 eq. In 2008, the estimated total electricity consumption, energy consumption and GHG emissions from Chinese white-leg shrimp production would be 1.1 billion kilowatt hours, 49 million GJ and 4 million tonnes, respectively. Consideration of my various impact levels and scenarios lead me to propose that semi-intensive production is the most sustainable system per tonne of production. Improvements suggested for Chinese shrimp aquaculture include changes in feed composition, farm management, electricity generating sources, and effluent treatment before discharge. Of course, any change in the management system affects overall performance and may make different systems show better sustainability performance.

Comparative LCA studies also indicate that farming systems with relatively lower intensity using more natural systems are more environmentally friendly. Semi-intensive farming outperforms intensive farming systems in LCA metrics. Closed recirculating systems outperform open systems in eutrophication emission and biodiversity reservation but all other environmental impact categories such as global warming and energy use are substantially worse. Polyculture systems have no advantage compared to monoculture in terms of environmental sustainability. Organic farming at low intensity seems to be a promising system if animal-derived ingredients are substituted with proper plant-based ingredients in the feed. By a comparison of captured and farmed seafood with agri-food products, agri-food products except chicken are usually more CO_2-intensive and perform worse in acidification and eutrophication than seafood products. Beef is the most CO_2-intensive and has the highest impacts in acidification and eutrophication. Wild-caught seafood is more energy-intensive than farmed seafood and agri-food. More comparative studies are needed to benchmark different aquaculture production systems and their seafood products to promote developing more sustainable aquaculture production systems. Due to differences in system boundaries, functional units, and impact assessment methodologies adopted, comparisons and interpretation should be done with caution.

Management strategies have significant impacts on nutrient dynamics and loading to receiving waters. Nutrient levels in the water column increase with system intensification. A combination of moderate stocking density and reduced water exchange rate would probably be the most optimistic scenario that could achieve a win-win situation with low nutrient loading while maintaining high shrimp production. To achieve

this win-win situation and realize truly sustainable shrimp production, future research should continue and concentrate on optimizing shrimp farming system to minimize environmental impacts and maintain/improve farm production.

Intensive farming systems show the highest profitability, followed by polyculture and semi-intensive farms. Management strategies including stocking density, aeration rate and feeding rate have significant influence on farm profitability. Disease outbreak has the largest influence on intensive farms and least influence on polyculture farms. Adopting best management practices (BMPs) or good management practices (GAPs) such as implementing effluent treatment in shrimp farming and participating in certification programs should be promoted, but challenges will exist, particularly for small- or medium-scale, family-operated farms. Further studies are needed to evaluate potential incentives for implementing good management practices such as financial aid or subsidy from the government. Social sustainability analysis concluded that people lived a happier life and considered their quality of life was improved by shrimp farming in the region.

In spite of considerable effort at quantifying ecological, economic and social sustainability of shrimp farming, I would like to give a qualitative summary based on my combined quantitative results to inform decision-maker in a rapid fashion. In addition to developing more quantitative and objective methods to evaluate the triple metrics of sustainability, economic and ecological interventions are needed to improve existing systems while evaluating future alternatives. These interventions may include increasing market value for certified products using GAPs or BMPs, better understanding of disease spread across aquaculture landscapes, better research on reducing effluent effects of

intensive systems. Ideally, the most responsible system overall may be an intensive system which follows GAPs or BMPs to use moderate stocking density, reduced or no water exchange, and minimized animal-derived feed ingredients.

APPENDIX

Table A1 Key characteristics of different shrimp supply chains in the study.

Stage	Intensive supply chain	Semi-intensive supply chain
Hatchery	– Import Hawaii SPF (specific-pathogen free) broodstock by air – Produce F1(1st generation) post-larvae with higher survival & growth rates – Industrial-scale, commercial based	– Use local domesticated broodstock – Produce F2 (2nd generation) post-larvae with lower survival & growth rates – Small-scale, family based
Grow-out	– Use F1 post-larvae – High stocking density (160-200 post-larvae/m^2) – High water exchange rate (8%-15% daily) – Frequent aeration – No fertilizer used – High feed conversion ratio (FCR), average 1.6 – Culture cycle: 100 days/crop – High unit production (8,000 kg/ha)	– Use F2 post-larvae – Medium-low stocking density (50-80 post-larvae/m^2) – Low water exchange rate (1%-3% daily) – Rare aeration – Fertilizer used – Low FCR, average 0.97 – Culture cycle: 100-120 days/crop – Low unit production (2,500 kg/ha)
Post-farming	– Processed as head-off ,shell-on frozen shrimp – Export to US	– Processed as head-off, shell-on frozen shrimp – Sell in domestic markets

Table A2 Background processes and associated data sources.

Inventory material	Data source
Infrastructure	
Concrete	Ecoinvent v 2.0 database[*]
LDPE[1]	Ecoinvent v 2.0 database[*]
HDPE[2]	ETH-ESU 96 database[*]
Steel	ETH-ESU 96 database[*]
PVC[3] pipe	Industry data 2.0 database[*]
Fuel	
Diesel	Ecoinvent v 2.0 database[*]
Electricity generation	
Coal	Ecoinvent v 2.0 database[*]
Hydro	Ecoinvent v 2.0 database[*]
Natural gas	Ecoinvent v 2.0 database[*]
Nuclear	Ecoinvent v 2.0 database[*]
Water quality inputs	
Chlorine	ETH-ESU 96 database[*]
Lime	ETH-ESU 96 database[*]
Limestone	Ecoinvent v 2.0 database[*]
Feed ingredients	
Corn starch	BUWAL250 database[*]; Pelletier et al. 2009
Fish meal	LCA food database[*]; Pelletier et al. 2009
Fish oil	Pelletier et al. 2009
Soybean meal	Ecoinvent v 2.0 database[*]; Pelletier et al. 2009
Wheat flour	LCA food database[*]; Pelletier et al. 2009
Packaging	
Plastic bag	Ecoinvent v 2.0 database[*]
Paper box	Ecoinvent v 2.0 database[*]
Ice	LCA food database[*]
Other	
EDTA[4]	Ecoinvent v 2.0 database[*]
Egg	LCA food database[*]
Steam	Ecoinvent v 2.0 database[*]

Notes: [1]Low-density polyethylene; [2]High-density polyethylene; [3]Polyvinyl chloride; [4]Ethylene Diamine Tetraacetic Acid; [*] Available within Simparo 7.1 (PRé, *2008.*)

Table A3 Inputs and outputs for production of 1 tonne of shrimp feed in China in 2008.

Inputs/Outputs	Components	Value
Inputs	Fish meal (kg)	422
	Wheat flour (kg)	240
	Soybean meal (kg)	110
	Corn starch (kg)	85
	Squid meal (kg)	40
	Fish oil (kg)	28
	Binder[*] (kg)	20
	Soybean lecithin[*] (kg)	18
	Mineral premix[*] (kg)	15
	Vitamin premix[*] (kg)	15
	Cholesterol[*] (kg)	5
	Vitamin C[*] (kg)	2
	Plastic packaging LDPE (kg)	5
	Water (l)	750
	Electricity (MJ)	630
	Diesel (MJ)	176
	Steam (kg)	250
Outputs	Suspended Solids (kg)	0.006
	BOD (kg)	0.0015
	COD (kg)	0.0028
	Total N (kg)	0.0006
	Total P (kg)	0.00013

Notes: [*]denotes that those ingredients under 5% of the total were not included in the LCA analysis.

Table A4 Life cycle inventory data for the production of 1 tonne of shrimp larvae (0.005 g/larvae) in China in 2008.

	Materials	Industrial-scale hatchery using imported broodstock	Small-scale hatchery using domesticated broodstock
Inputs-infrastructure[4]	HDPE[1] liner (kg)	9.8	19.4
	Concrete (m^3)	22.6	38.6
	PVC[2] pipe (kg)	72	123
	LDPE[3] cover (kg)	593	1010
	Steel pipe (kg)	47.8	79.6
Inputs-operational	Brookstock[5] (kg)	88.1	144
	Fresh water (l)	47,500	75,200
	Sea water (l)	119,000	188,000
	Chlorine (kg)	2.4	3.8
	Egg yolk (kg)	2,000	2,000
	Feed (kg)	8,800	11,800
	EDTA[6] (kg)	1.2	1.8
	Electricity (kwh)	30,800	26,800
Outputs-operational	BOD_5 (kg)	34.2	53.4
	NO_2 (kg)	0.2	0.4
	NO_3 (kg)	3	4.4
	Ammonia (kg)	0.2	0.4
	Total Phosphorous (kg)	1.14	1.66

Notes: [1]High-density polyethylene; [2]Polyvinyl chloride; [3]Low-density polyethylene; [4]We assumed that shrimp farms had 20 years of lifespan and annualized the material production, maintenance and end of life impacts to ultimately calculate impacts per functional unit. [5] Broodstock: To produce 1000 kg live-weight of shrimp, only 0.095 kg of imported broodstock was needed for intensive systems and 0.14 kg of local broodstock was needed for semi-intensive systems. Thus we assumed that broodstock production was negligible and excluded from our system boundaries. [6] Ethylene Diamine Tetraacetic Acid.

Table A5 Life cycle inventory data for processing and packaging of 1 tonne of frozen headless shell-on shrimp in China in 2008.

Input	Value
Shrimp (live-weight, kg)	1,200
Water (l)	12,500
Plastic bag (kg)	10.5
Paper box (kg)	135
Ice (kg)	1,500
Electricity (kwh)	550

Table A6 Transportation of imported broodstock from Hawaii and local domesticated broodstock.

	Unit	Hatchery using imported broodstock	Hatchery using local domesticated broodstock
Transport distance	km	50 km by truck (from Hawaii farm to Hawaii airport) 7,900 km by freight air (from Hawaii to Hainan) 100 km by truck (from Hainan airport to Hainan hatchery)	100 km by truck (from Hainan farm to Hainan hatchery)
Broodstock number	Pairs	370	480
Total broodstock weight	kg	44.4	43.2
Ice	kg	92.5	60
Carton boxes	kg	139	90
LDPE film bag	kg	11.1	7.2
Sea water	l	1,850	1,200

Table A7 Transportation of raw material for production of 1 tonne of shrimp feed (assumes 50% of fishmeal and squid meal imported from Peru are used, with another 50% of each from local companies).

Raw materials	Distance	Unit	Route	Weight	Unit
Imported fishmeal	8,500	km	By freight air, Peru to Hainan	211	kg
	100	km	Hainan airport to feed mill	211	kg
Imported squid meal	8,500	km	By freight air, Peru to Hainan	40	kg
	100	km	Hainan airport to feed mill	40	kg
Fishmeal	100	km	Hainan-feed mill	211	kg
Fish oil	100	km	Hainan-feed mill	28	kg
Wheat flour	100	km	Hainan-feed mill	240	kg
Soybean meal	100	km	Hainan-feed mill	110	kg
Corn starch	100	km	Hainan-feed mill	85	kg

Table A8 Feed transport for 10,000 larvae and 1 tonne of live-weight shrimp production.

	Hatchery 1	Hatchery 2	Intensive	Semi-intensive
Feed weight (kg)	0.44	0.59	1,600	970
Transport distance (km)	100	100	100	100

Table A9 Fertilizer and chemical transport for producing 1 tonne live-weight of shrimp.

	Intensive	Semi-intensive
Fertilizer weight (kg)	0	3,550
Chemical weight (kg)	1,440	709
Transport distance (km)	100	100

Table A10 Larval transport.

8,000 of larvae (kg)	0.04
Sea water (l/bag)	10
LDPE bag (kg)	0.06
Total weight (kg)	10.1
Transport distance (km)	100

Table A11 Post-farming transport, including transport from farm to processing plants, from processing plants to Hainan Port, and to destination ports.

	Farm to processing plants	Processing plants to destination ports
Intensive	100 km by truck	100 km from the processing plant to Hainan port by refrigerated trucks 18, 500 km to Chicago port by ocean freighter
Semi-intensive	100 km by truck	100 km from the processing plant to Hainan port by refrigerated trucks 2,500 km to Shanghai port by ocean freighter

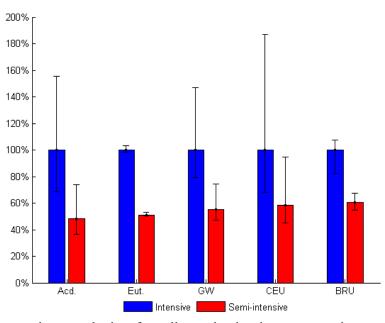**Table A12** Sensitivity analyses and scenario model outcomes for cradle-to-destination-port emissions.

LCIA Methodology	Impact category	Unit	Intensive	Semi-intensive
IMPACT 2002+	Acd.	kg SO_2 eq	59.1	28.6
	Eut.	kg PO_4 eq	28	12.1
	GW	kg CO_2 eq	6,600	3,720
Eco-indicator 95	Acd.	kg SO_2 eq	59	28.5
	Eut.	kg PO_4 eq	64.9	33.1
	GW	kg CO_2 eq	6,570	3,670
CML2 Baseline 2000	Acd.	kg SO_2 eq	56.7	27.4
	Eut.	kg PO_4 eq	64.9	33.1
	GW	kg CO_2 eq	6,930	3,840

Table A13 Environmental impact comparison of different food products based on global warming potential and energy consumption per kilogram of product.

	CO_2 eq (kg)	CEU (MJ)	References
Beef	28	276	Nemecek and Gaillard, 2009
Pork	11	193	Nemecek and Gaillard, 2009
Poultry	3.6	65	Nemecek and Gaillard, 2009
Farmed salmon	2.8	98	Ayer and Tyedmers, 2009
Trout	2.7	78	Aubin *et al.,* 2009
Sea bass	3.6	55	Nemecek and Gaillard, 2009
Thai farmed shrimp	5.1	46.5	Mungkung, 2005; Mungkung and Gheewala, 2007
Chinese farmed shrimp	**3.1**	**38.3**	Present study (average values)
Tilapia	2.1	26.5	Pelletier and Tyedmers, 2010

Table A14 Comparison of estimated model parameters.

Nutrient dynamics parameters	Current study	Burford and Lorenzen, 2004
s (sinking rate of dead algae, % day^{-1})	6.4	80
n (nitrification rate, % day^{-1})	9.9	15
v (volatilization rate, % day^{-1})	4.8	5
g_{max} (maximum algae daily growth rate, day^{-1})	0.59	1.45
I_{ratio} (ratio surface/saturation light intensity)	0.83	2.4
k_{SN} (N half-saturation, mg l^{-1})	0.0043	0.008
k_{SP} (P half-saturation, mg l^{-1})	0.0036	-
c (nitrogen-to-Chl ratio)	4.8	13
u (phosphorus-to-Chl ratio)	2.1	-
b_P (allometric scaling of TP input)	0.69	-

Figure A1 Uncertainty analysis of cradle-to-destination-port environmental impacts (1 tonne of shrimp) using Monte Carlo simulation with set stop factor of 0.005 to generate 95% confidence intervals.
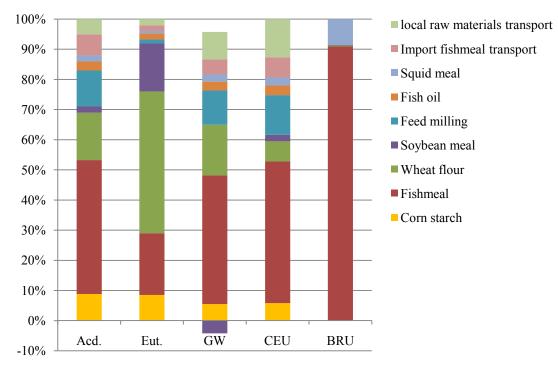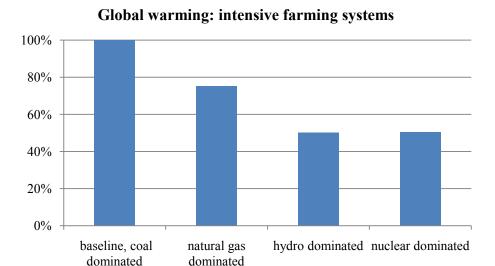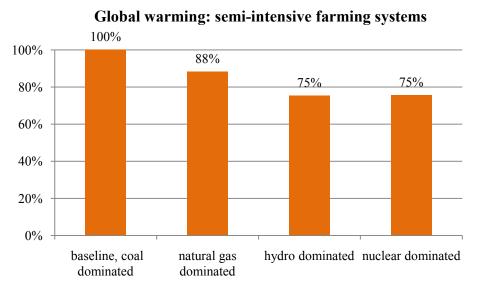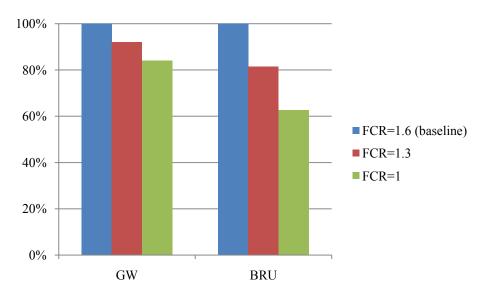

Figure A2 Contribution analysis of 1 tonne of shrimp feed production.
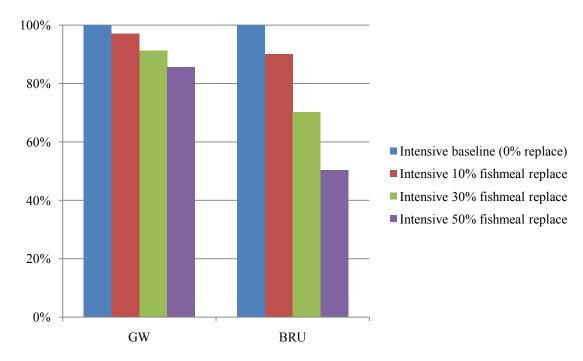
Global warming: intensive farming systems

Figure A3 Sensitivity analysis of country-specific electricity mix profile (1 tonne live-weight of shrimp produced from intensive farming).

Global warming: semi-intensive farming systems

Figure A4 Sensitivity analysis of country-specific electricity mix profile (1 tonne live-weight of shrimp produced from semi-intensive farming).

Figure A5 Sensitivity analysis of feed conversion ratio for 1 tonne live-weight of shrimp produced in intensive farming systems.

Figure A6 Sensitivity analysis of fish protein replaced by plant protein for 1 tonne live-weight of shrimp production in intensive farming systems.