LIFE CYCLE ASSESSMENT OF INDOOR RECIRCULATING SHRIMP AQUACULTURE SYSTEM

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Abstract

This study analyzed the sustainability and environmental impact of indoor recirculating aquaculture systems (RAS) used for raising shrimp in the U.S. A life cycle analysis (LCA) was performed to evaluate the environmental and energy performance of the system. In the LCA study, the functional unit was 1800 kg fresh shrimp, produced by a commercial-scale recirculating shrimp aquaculture system in the U.S. The life cycle model included the hatchery, recirculating farm, product processing & storage, and transportation stages. The impact assessment method used was Eco-Indicator 95 and the environmental impact categories included global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), heavy metals (HM), carcinogens, pesticides (PC), summer smog (SS), winter smog (WS) and solid waste (SW). According to the LCA results, shrimp farming accounted for 95% of the life cycle energy use and caused 82-99.6% of the environmental impacts in the life cycle system.

A scenario analysis examining transportation, marketing, farm location, and biosolids handling was also conducted. Results were sensitive to farm location and marketing scale while transportation and biosolids handling were much less significant. Reducing the scale of the market reduced environmental impacts due to energy savings in product distribution and storage. Impacts of the local-scale scenario were just 42-87% of those of the national-scale scenario. Farm location was also significant since the energy use and environmental impacts in mainland coastal farms were 30% and 9-37% of those in the inland farms, respectively. With the same culture technique and product distribution, coastal farms were preferable to inland farms in terms of energy savings and pollution reduction. Moreover, compared to culturing shrimp locally in Michigan, buying shrimp from the Southern coast reduced life cycle energy by 70% and reduced pollutant emissions by 86-643% for Michigan consumers. In addition, for American consumers, producing shrimp in this country was recommended, over importing shrimp from Asia. Shrimp production and distribution in the US led to a 15-82% reduction in pollutant emissions.

In comparing culture technique, there was a trade-off amongst energy consumption, water use, and environmental impacts with RAS and conventional flow-through farms. The RAS used 70% less water than the conventional system, while the electricity usage in RAS was 1.4 times that of the conventional flow-through system. The RAS produced lower GWP, EP, and ODP impacts while the conventional farm showed better performance in terms of AP impacts.

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1 Introduction

1.1 Overview

1.1.1 Seafood production and sustainability

Capture fisheries and aquaculture supplied the world with about 106 million metric tons of food fish in 2004, providing an apparent per capita supply of 16.6 kg (live weight equivalent), which is the highest quantity on record (FAO, 2007). Of this total, aquaculture accounted for 43 percent. Aquaculture production has increased at an average annual growth rate for the world of 8.8 percent per year since 1970. Aquaculture production in 2004 was reported to be 45.5 million metric tons, with a value of US$63.3 billion (FAO, 2007). Rising global demand for seafood and declining catches have created a new impetus to expand seafood production through aquaculture.

1.1.2 Case of shrimp

Total world trade in fish and fishery products reached a record value of US$71.5 billion (export value) in 2004, representing 23 percent growth relative to 2000 (FAO, 2007). Shrimp was the most important commodity traded, in value terms, accounting for 16.5 percent of the total value of internationally traded fishery products in 2004 (FAO, 2007). The substantial increase in the quantity of shrimp traded coincided with strong expansion in aquaculture shrimp production, which has grown rapidly since 1997, with an increase of 165 percent from 1997 to 2004 (annual growth of 15 percent). In 2004, more than 41 percent (or 2.5 million metric tons) of total shrimp production was of farmed origin (FAO, 2007).

Shrimp aquaculture can help to reduce pressure on overexploited wild stocks, in terms of natural resources protection. However, due to poor planning and management as well as a lack of appropriate regulations, shrimp aquaculture itself may have several adverse environmental impacts. Most of the land used for shrimp ponds previously comprised salt marshes, mangrove areas and agricultural lands (Paez-Osuna, 2001). Since the effluents from shrimp aquaculture typically are enriched in suspended solids, nutrients, chlorophyll a and biochemical oxygen demand (BOD), the effluents often contribute to eutrophication of receiving waters (Dierberg & Kiattisimkul, 1996; Paez-Osuna et al., 1998). Diseases are also recognized as the biggest obstacle to the future of shrimp aquaculture. Diseases in farms and hatcheries are caused by the invasion of protozoa, fungi and bacteria, but viral diseases provoke the greatest losses (Paez-Osuna, 2001). Other environmental impacts of shrimp aquaculture include: exotic shrimp introductions, salt water intrusion due to active pumping of groundwater into coastal ponds, disposal of sediments from culture ponds with accumulated nutrients and other chemicals, and escapement of aquatic crops and their hazard as invasive species.

Environmental awareness and concerns about sustainability of shrimp culture became increasingly important to the informed public during the 1990s. Given the potential adverse impacts and the large economic value of shrimp aquaculture, innovative techniques and integrated management are needed. Stringent government regulations and increased awareness of the impacts of effluents on receiving waters have encouraged the development of new technologies and innovations, helping to make the aquaculture industry more sustainable and economically viable (Boyd et al., 1998). Some methods have been developed to help to improve the water quality in discharge water, such as recirculating systems (Rosati & Respicio, 1999), constructed wetlands (LaSalle et al., 1999), and better feeds and feeding practices (Cho & Bureau, 1997). These innovations can reduce the load of organic matter and biosolids in aquaculture effluent (McIntosh & Fitzsimmons, 2003).

1.1.3 RAS as more sustainable shrimp culture

The technology of recirculating aquaculture systems (RAS), shown in Figure 1, has been under development and refinement for the past thirty years to address many environmental challenges. RAS potentially alleviates deleterious effects of fish farming on the environment for the following reasons: (1) Water circulates throughout the system such that the total water consumption is reduced; (2) RAS requires much less land than a conventional aquaculture system; (3) RAS enables climate control and allows year-round production with consistent volumes of product, giving RAS a competitive advantage over outdoor systems; (4) Recirculating shrimp systems are usually located inland and use municipal water for artificial seawater preparation, so risk of disease is reduced. Reduced water exchange also reduces disease introduction. (5) Because of excellent water quality, shrimp can be grown in recirculating systems at very high densities. On the other hand, RAS also has some disadvantages, such as high initial investment, complexity and high energy requirements.

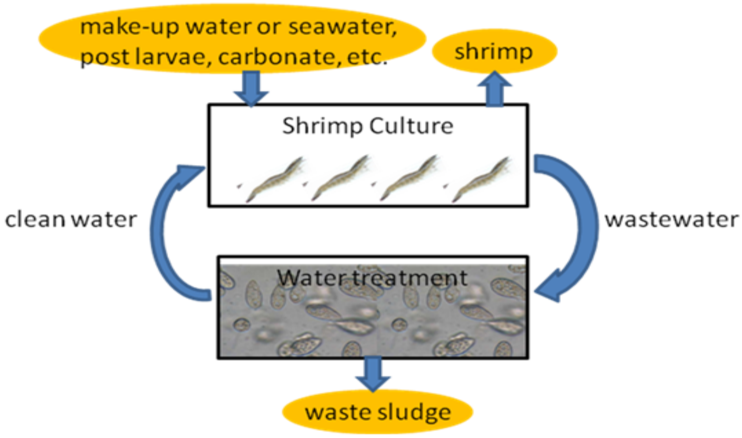


Figure 1 Schematic of a recirculating aquaculture system consisting of shrimp culture system and water treatment system.

1.1.4 LCA methods to evaluate sustainability

Life cycle assessment (LCA, also known as life cycle analysis, ecobalance, and cradle-to-grave-analysis) methods are described in a series of the ISO 14000 environmental management standards. LCA is a rigorous framework for conducting cradle-to-grave assessments of the environmental impacts associated with the production and distribution of consumer goods. LCA quantifies material and energy flows across all stages of a product's life. LCA evaluates the cumulative environmental impact resulting from all stages in the product life cycle. LCA methodology lends itself to a unified, integrated accounting system that makes transparent the environmental and socioeconomic costs of various seafood production processes.

An LCA study consists of four sequential components: goal definition and scoping, inventory analysis, impact assessment and interpretation (Figure 2). Goal definition and scoping requires mapping of the intended application, the reason for the study, the intended audience, the functional unit and system boundaries. Inventory analysis involves compilation and quantification of inputs and outputs throughout the life cycle. Impact assessment evaluates the magnitude and significance of potential environmental impacts of a product system. Interpretation combines the findings of the inventory analysis and impact assessment in order to draw conclusions and present recommendations.

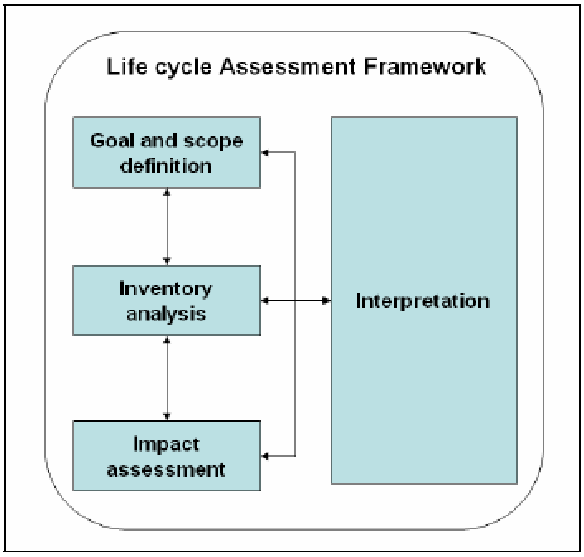


Figure 2 Life Cycle Assessment Framework (from ISO 14040 Standards)

For aquaculture systems, LCA provides a useful model of these complex systems by quantifying and describing interactions of system components. It offers a comprehensive environmental profile of the system as well as a more transparent view of inefficient or potentially damaging production practices. LCA assesses the energy and materials used in production, as well as the wastes released, to evaluate the impact of the entire process on the environment. Additionally, it highlights opportunities in the production cycle for environmental improvements. However, as the application of LCA to aquaculture is a recent development, only a few case studies of LCA in aquaculture have been reported so far.

- **Shrimp farming in Thailand**

Mungkung (2005) conducted an environmental LCA of shrimp farming in Thailand, which included hatchery, farming, processing, distribution, consumption and waste management phases. The functional unit was a standard consumer-package size containing 3 kg of block-frozen shrimp. The system used wild-capture broodstock in the hatchery. The impacts assessed in this study were: abiotic depletion potential, global warming potential, ozone depletion potential, human toxicity potential, freshwater toxicity potential, marine toxicity potential, terrestrial toxicity potential, acidification potential, photochemical oxidant creation potential and eutrophication potential. The main impacts of shrimp culture were marine toxicity, global warming, abiotic depletion and eutrophication. Farming was the key life cycle stage contributing to the impacts. These impacts arose mainly from the use of energy, shrimp feed, and burnt lime. Transport of post-larvae from a non-local source to farms also resulted in significantly higher impacts. This study only analyzed conventional farming systems, and did not cover other farming technologies, such as recirculating shrimp aquaculture systems.

- **Rainbow trout culture in Finland**

Application of LCA to Finnish cultivated rainbow trout production was conducted by Gronroos et al. (2006). The functional unit was one metric ton of ungutted rainbow trout after slaughtering. The processes analyzed include raw material production for feed, feed manufacturing, packaging materials production, package manufacturing, hatchery, fish farming and slaughtering. Environmental impact categories included climate change, acidification, aquatic eutrophication, tropospheric ozone formation, and depletion of fossil fuels. The environmental performance of production methods with different feeds, feed coefficients, and pollution reduction measures were assessed. The results revealed that atmospheric emissions – originating mainly from raw material production, manufacturing and transportation of feed – made only a minor contribution to the total environmental impacts caused by production of rainbow trout in Finland. Phosphorus and nitrogen emissions from fish farms to waters were found to be the most significant emissions contributing to total impacts. The major limitation of this LCA was the incomplete scope of analysis, as the study did not include the stages of fish processing, retail, or waste management.

- **Recirculating production of turbot in France**

The environmental impacts of a water recirculating system for fish farming were studied by Aubin et al. (2006) through the case study of an inland turbot farm located in Brittany (France). Environmental impacts were analyzed using the following indicators: eutrophication potential, acidification potential, global warming potential, net primary production use and non-renewable energy use. This research only analyzed the turbot farming stage, while environmental assessment requires integrative approaches that take into account all the stages and processes and includes their potential environmental impacts at the local, regional and global scale.

Two methods were used to assess the farm's nitrogen, phosphorus and solids emissions: nutrient measurement accounting and nutrient balance modeling. The two methods gave similar results for solids and phosphorus emissions, while for nitrogen the measurement-based approach only accounted for half the emissions predicted by the model. The uncertainty regarding the potential gaseous nitrogen emissions led the authors to assess impacts according to three scenarios differing with respect to emissions of N_2, N_2O and NH_3. The uncertainty concerning nitrogenous emissions to the atmosphere led to uncertainty with respect to the production system's eutrophication and global warming potentials. Comparison of the results with similar results for production of large rainbow trout in a flow-through system indicated that non-renewable energy use of the turbot re-circulation system was 4 to 6.5 times higher. The acidification potential and global warming potential in two re-circulating system scenarios were three times higher than those of flow-through trout production.

- **Trout farming in France**

Papatryphon (2004) assessed the environmental impacts associated with different feed for rainbow trout production in France, using LCA. The functional unit was the amount of feed required for the production of one metric ton of rainbow trout. To allow comparison on an equivalent basis, the four analyzed feeds were considered in terms of a normalized nutrient profile (40% crude protein, 26% fat, 19.5 kJ/g digestible energy).

The stages assessed were: extraction of raw materials, production and transformation of primary ingredients used, manufacture of feeds, use of feeds at the farm, transport at all stages, and production and use of energy resources. The assessment revealed that use of fishery resources (such as biotic resource use) and nutrient emissions at the farm (such as eutrophication potential) contributed most to the potential environmental impacts of salmonid aquafeeds. Improvements in feed composition and management practices seem to be the best ways to improve the environmental profile of aquafeeds. However, waste management was not assessed in any stage.

To date, none of these research projects analyzed the life cycle performance of shrimp produced by a recirculating system or waste management recirculating system. Comparison of RAS with conventional flow-through farming system has not been conducted either.

1.2 Purpose of study

This study focuses on shrimp culture using indoor recirculating systems located in the United States. The primary objectives are:
(1) to conduct an LCA to evaluate environmental and energy performance of RAS;
(2) to compare the environmental impact results with other shrimp production systems;
(3) to evaluate the specific sources of impacts; and
(4) to recommend opportunities for improvement of the system.

2 Goal Definition and Scoping

The functional unit of this LCA is 1000 bags of fresh or frozen whole shrimp. One bag of shrimp contains approximately 1.8 kg shrimp, so the functional unit is equivalent to 1800 kg of shrimp. The following stages were analyzed for the indoor recirculating shrimp aquaculture system: 1) Hatchery, 2) Indoor Recirculating Shrimp Farm (consisting of the shrimp culture system and water treatment system), 3) Processing & Storage, and 4) Transportation (Figure 3 and Figure 4). Baseline (Alternative 1) was a local-scale scenario, which included the hatchery, farm and transportation stages. National-scale production was considered in the marketing scale scenario analysis. The national-scale scenario included the hatchery, farm, processing & storage, and transportation stages. Shrimp consumption was not included in the assessment. Material consumption, energy use and waste disposal were evaluated within the individual life cycle stages, where appropriate.

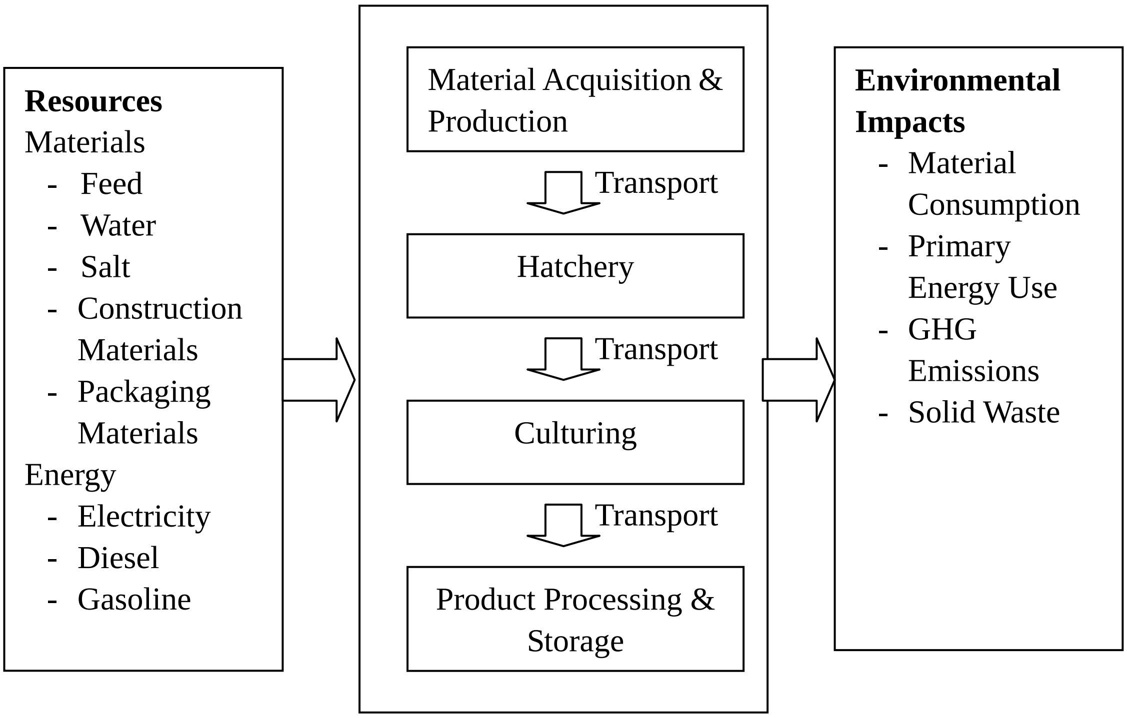


Figure 3 A life cycle schematic of the recirculating shrimp aquaculture system, analyzed in this thesis.

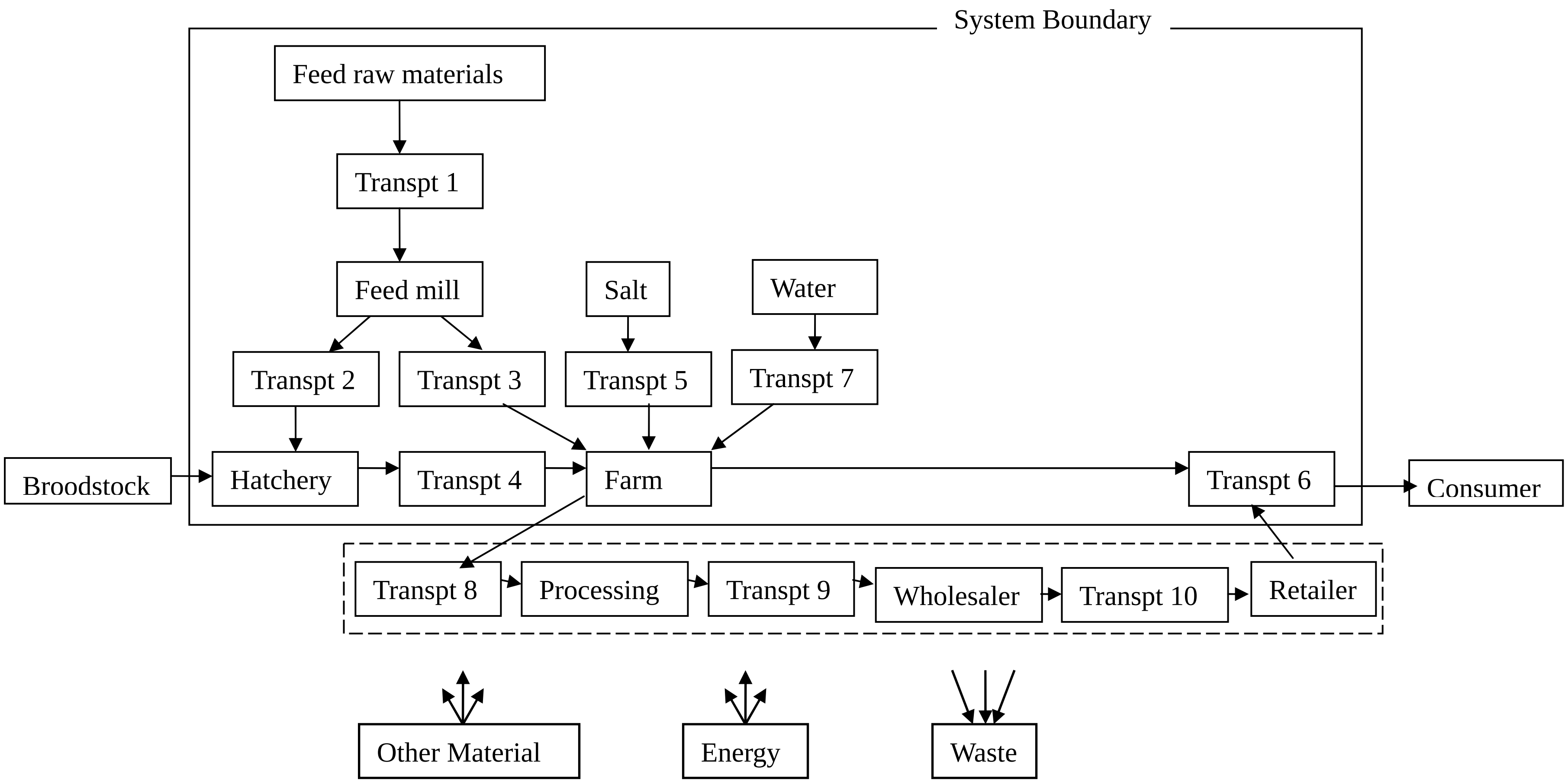


Figure 4 Detailed life cycle of recirculating shrimp aquaculture system, which highlights the scope of this thesis (excludes brood stock production and consumer stages).

2.1 Hatchery

At a hatchery, broodstock was cultured to post larvae (PLs) which were prepared for shrimp culture farms. In this study, data was collected at hatcheries in China (Ling Cao, personal communication). The source of broodstock was Hawaii and Miami. Larvae were cultured in small concrete rectangular tanks. Seawater was pumped from a central reservoir. Water was removed by siphoning or through a drain during tank cleaning. The culture environment in the hatchery system was controlled at 33 ppt salinity, 27-32° C temperature and pH of 8.0-8.3 (Forbes, 1992). Hatcheries were typically equipped with thermometers, a pH meter, and a microscope which helped to control the culturing environment (Forbes, 1992). Electricity was consumed by several types of equipment, including aerators and water pumps.

In the hatchery, the first larval stage of eggs transformed to nauplii after one day of hatching. After feeding on their reserves for a couple of days, the nauplii morphed to the second larval stage, where the primary visible features are feathery appendages and elongated bodies. Then, the second-stage larvae transformed to the final stage, with segmented bodies, eyestalks and shrimplike tails (Bailey-Brock & Moss, 1992). After three or four days they became post-larvae (PL), which resemble adult shrimp. Usually, PLs were introduced into the grow-out system around 20 days after hatching.

2.2 Recirculating Aquaculture Farm

The activities involved in the shrimp culture farm were based on surveys of a research farm maintained by the Oceanic Institute (41-202 Kalanianaole Highway, Waimanalo, HI 96795). This farm used a recirculating shrimp aquaculture system. Data from this farm was extrapolated to a scale suitable for commercial production, and used in this study to model a recirculating system. The modeled system was assumed to be located in Texas 4 km from the Gulf of Mexico coast.

At the Oceanic Institute, PLs from the hatchery were stocked into rectangular culture tanks. The carrying capacity of the system was 10 kg shrimp / m^2. The farm modeled in this study consisted of 90 tanks, which each measure 300 m^2 and are 1.6 m deep. Ten tanks were included in one enclosed building that covered approximately 5000 m^2 of land (Figure 5). A feasible production volume was assumed to be 800 metric tons per year, so a farm would require 9 buildings of these dimensions. The environment within the building was controlled year-round at a temperature of 23-34° C. During the culturing period, oxygenation was used to maintain dissolved oxygen levels at 5 mg/L in the tanks. In the water reuse system, all effluents from the shrimp tanks passed through a sedimentation tank or settler. Resident time of water in the settler was one hour, after which the water was returned to the shrimp culture tanks.

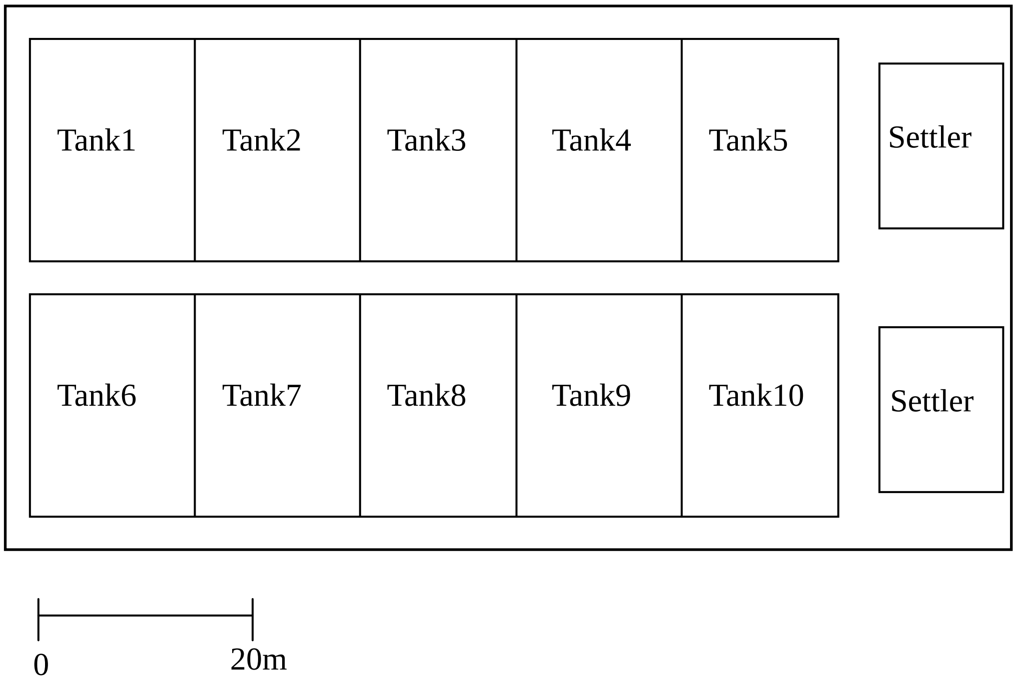


Figure 5 Layout of Oceanic Institute Farm Building, including 10 tanks for shrimp culture and 2 settlers for water treatment.

Sedimentation (i.e. gravity separation) was one of the simplest technologies available to control the particulate solids in the process water and wastewater. The continuous flow settling basins can be functionally divided into four zones according to their function (Figure 6). The inlet zone served to uniformly distribute the suspension over the entire cross-section of the basin. Sedimentation occurred in the settling zone and the suspended solids and flocs accumulated in the sludge zone. The clarified liquid was generally collected over the entire cross-section of the basin at the outlet zone and discharged.

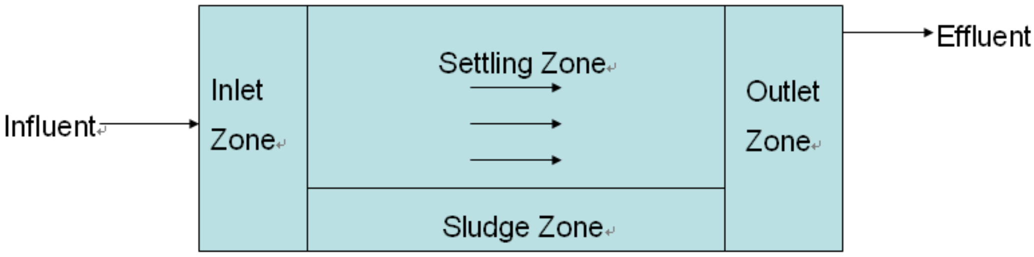


Figure 6 A schematic of four principal zones of a rectangular continuous flow sedimentation basin

The shrimp production cycle from PLs to market-size shrimp normally takes about 15 weeks, so a given year could have 3.5 culture cycles. The composition of water used in the system depended on farm location and distance from the coast. Water consumption was 480m^3/day – 10 % of the total water in the system. Bicarbonate was used to maintain water quality, so that the pH in the tank remained between 6.5 and 7.

A computer spreadsheet was used to design the commercial-scale recirculating shrimp culture system (Losordo & Hobbs, 2000). Most design parameters and assumptions used in the model were based on a data survey completed by the Oceanic Institute (survey questions were provided in Appendix 1). If data based on the actual operation were unavailable, assumptions were made based on the literature. The design spreadsheet, including key parameters and assumptions, are shown in Appendix 2.

2.3 Feed

The hatchery and farm were assumed to use shrimp feed of the same composition but different size. The formulated shrimp feed analyzed in this study met the nutrient requirements of shrimp used in the research farm. Feed producers were unwilling to provide their precise formulas because they are proprietary. Therefore, a formulation for the shrimp feed and associated raw materials (Table 1) were developed for this model based on Hernández et al. (2008). Processing 1 metric ton of feed consumed 2646 kWh of electricity (Papatryphon et al., 2004). Waste output data (Table 1) were from Silvenius and Grönroos (2003). Since electricity consumption was determined primarily by the concentration of nutrients and organic matter in the wastewater, the electricity used for wastewater treatment was calculated based on net electrical consumption associated with treatment of organic matter, set as 1.1 kWh per kg COD removed based on the LCA food DK database (www.lcafood.dk). Table 2 lists the proximate composition of the shrimp feed (Hernández et al., 2008).

Table 1 Raw materials, electricity use and waste emissions for producing 1 metric ton of shrimp feed

Raw Materials	**%**	**kg**
fishmeal	42.20	422
wheat flour/gluten	26.00	260
core starch	12.61	126
soybean meal	6.44	64
fish oil	2.80	28
squid meal	2.00	20
Binder	2.00	20
soybean lecithin	1.75	18
Vitamin premix	1.50	15
mineral premix	1.50	15
Cholesterol	0.50	5
Chromic oxide	0.50	5
Vitamin C	0.20	2
total	100.00	1,000
Electricity	**kWh**	
Feed Production	2,646	
Waste Treatment	0.343	
Waste Outputs	**kg**	
Airborne emissions		
particulates	0.48	
Waterborne emissions		
COD	0.312	
waste water	180	
Solid wastes		
waste to rubbish dump	5.186	
waste, composted	2.078	
waste, hazardous waste	0.243	
waste, water sludge	1.172	

Table 2 Proximate composition of shrimp feed

Proximate analysis	**(% dry basis)**
Moisture	8.8
Crude protein	35.6
Crude fat	9.3
Ash	10.8
NFE	44.3
Gross energy (kcal/100g)	450.8

2.4 Processing and Storage

Local-scale (Alternative 1) and national-scale (Alternative 2) scenarios were analyzed in the product marketing life cycle phase.

In the local-scale marketing scenario (Alternative 1), shrimp products were sold directly to local consumers at the farm. The main activities in this process were product chilling and transportation from farm to consumers. The national-scale marketing scenario (Alternative 2) more closely resembled a commercial production and a large-scale marketing system. In this scenario, whole shrimp were pre-frozen at the farm or processing plant before being transported to wholesalers by refrigerated truck,. The frozen shrimp was stored in freezers at wholesalers and retailers for 30 days and 10 days, respectively. At the retailers, such as supermarkets, the frozen shrimp were thawed in paper boxes and presented on ice in a refrigerated cabinet for sale.

2.5 Transportation

The LCA included transportation of raw materials (i.e. feed, salt, water) and transportation between the hatchery, farm, processing plant, wholesaler, retailer and consumer stages. A detailed description of each transportation stage is discussed in Section 3.1.4.

3 Life Cycle Inventory Analysis

3.1 Material Consumption at Each Stage

3.1.1 Hatchery

Most of the culture farms had their own hatcheries onsite, so the transportation distance for PLs from hatchery to farm was considered to be zero. Due to limited data on hatcheries in the U.S., it was assumed that the main activities involved in this stage were the same as those in China. Inputs, outputs and electricity consumption for the production of 1000 PLs in the hatchery are presented in Table 3. These values of hatchery inputs were based on a survey conducted by Ling Cao (personal communication) in Hainan Island, China. The input data used in the LCA were average inputs from three hatcheries of different size. Production of 1000 PLs required 0.0074 broodstock (the detailed calculation method is presented in Appendix 3). The output and emission data in the table were taken from the Thailand shrimp LCA study (Mungkung, 2005).

Due to limited environmental impact data, the following inputs and outputs were not included in the impact assessment of the hatchery: brood stock growth, suspended solids and total phosphorus treatment. The items analyzed for the hatchery LCA included consumption of water and feed, electricity used for the hatchery operation, and wastewater effluents (BOD and nitrogen).

Table 3 Inputs, outputs and electricity consumption for production of 1000 PLs in the hatchery. Data were from Chinese shrimp hatcheries (Ling Cao, personal communication) and Thailand shrimp hatcheries (Mungkung, 2005)

Inputs				
Hatchery	A	B	C	average
Hatchery size	large	middle	small	
broodstock (each)				0.0074
seawater (m^3)	0.143	0.834	0.193	0.390
feed (kg)	1.2			1.200
electricity (kWh)	0.320	0.247	0.498	0.355
Outputs/Emissions				
Suspended Solids (g)	2.76			
BOD (g)	0.16			
NO_2 (g)	0.001			
NO_3 (g)	0.013			
Ammonia (g)	0.002			
Total P (g)	0.005			
electricity used to treat wastewater (kWh)	0.00022			

3.1.2 Farming

Table 4 presents material consumption for facility construction and shrimp culture operation at the model farm. The table indicates the construction materials used for one greenhouse with shrimp culture tanks and sedimentation tanks. Service life for construction materials was assumed to be 25 years. The annualized values reported in the table were calculated by dividing total construction materials by 25. Inputs and outputs for shrimp culture listed in the table are for producing 84,000 kg of shrimp, which is the shrimp production per year per greenhouse. Inputs for shrimp culture included feed, water, PLs (the shrimp larvae themselves) and electricity. Since the farm was located close to the coast and used only seawater, the consumption of salt and freshwater for creating artificial seawater was zero. The outputs of the system include biosolids, wastewater and CO_2. In the baseline scenario, biosolids were transported to a landfill 75 km away. Biosolids handling processes included dehydration, liming, storage and transportation (Houillon and Jolliet, 2005). This RAS farm had a liquid discharge of 174,751m^3/year. The nutrients concentration in the effluent was estimated based on Piedrahita (2003). The electricity consumption for wastewater treatment was assumed as 4 kWh per kg nitrogen removed based on the LCA food DK database (www.lcafood.dk). The impact assessment in Section 4 includes the production of LDPE greenhouse covers, lumber (sawn timber, plywood) for posts and beams, concrete for tanks, PVC pipes, feed, PLs, electricity for shrimp culturing, biosolids treatment, and CO_2 emissions.

In the RAS farm system, phytoplankton consumed CO_2, nitrifying bacteria produced CO_2 and consumed NH_3, and shrimp generated CO_2 and NH_3 gas during their growth. It was assumed that the phytoplankton produced 2mgO_2 •L^{-1} •hr^{-1} (Burford et al., 2003), the ratio of O_2 to CO_2 was 1:1, and 2.8mgCO_2 •L^{-1} •hr^{-1} was consumed by photosynthesis. Thus, to produce 1800 kg shrimp (the functional unit in this study), phytoplankton consumed 2478 kgCO_2. Nitrifying bacteria converted 3.2mgN • L^{-1} • day^{-1} by nitrification (Rakocy et al., 2004), so 709 kg CO_2 was produced by nitrifying bacteria to produce 1800 kg shrimp. The amount of CO_2 generated by shrimp was based on the amount of feed and O_2 consumption. The feeding rate was set at 900 kg feed per day in each greenhouse (Appendix 2). Each unit of feed required 0.25 units of oxygen for fish metabolism (Timmons et al., 2002), thus 225 kg O_2 was consumed per day in each greenhouse. The production of 1800 kg shrimp generated 2420 kg CO_2 based on a calculation that assumed aerobic respiration. Therefore, taking the 2420 kg CO_2 generated by shrimp, plus 709 kgCO_2 generated by nitrifying bacteria, minus 2478 kg CO_2 consumed by phytoplankton, the net CO_2 emissions by RAS was 651 kg for 1800 kg shrimp production. This will be offset by carbon fixed in feed production.

Table 4 Construction materials, culture inputs, and waste production for one modeled greenhouse for one year

Material	**Amount**
Inputs for Construction	
LDPE greenhouse cover (kg)	138
sawn timber (m^3)	1.1
plywood (m^3)	0.002
concrete for tanks (kg)	139,594
HDPE liner (kg)	8,511
PVC pipe (kg)	117
Inputs for Culturing	
seawater(m^3)	175,200
feed (kg)	165,375
post larvae (#)	5,250,000
electricity (kWh)	370,404
Outputs	
biosolids (kg)	453,600
wastewater (m^3)	174,751
CO_2 (kg)	28,188

3.1.3 Processing and Storage

Two quite different alternatives for shrimp processing and storage were examined in this study. For the local marketing alternative (Alternative 1), 12.15 kWh of electricity was needed to keep 1800 kg chilled shrimp fresh for 10 days. Electricity consumption was calculated based on the cold storage energy requirement of 0.0025 MJ/L/day (Carlsson-Kanyama and Faist, 2000) and an estimated volume of 3.5L for 1.8 kg shrimp. Additionally, 9 kg of PET film was consumed for packaging 1800 kg of shrimp (Mungkung, 2005). For the commercial marketing alternative (Alternative 2), 1000 shrimp packages, weighing 1.8 kg each, would be transported to processing plants which were close (30 km) to the model farm. The shrimp were then frozen at the processing plant using a block freezing process, which required 1560 kWh of electricity (Mungkung, 2005). Then the frozen shrimp was transported to wholesalers and retailers by refrigerated-truck. The frozen shrimp was assumed to be stored for 40 days at wholesalers and retailers before being sold. Electricity was consumed by the freezers during storage at a rate of 0.0025 MJ/L/day (Carlsson-Kanyama and Faist, 2000), requiring a total of 97.2 kWh of electricity per 1800kg shrimp.

3.1.4 Transportation

There were 10 transportation stages for the production cycle in this model, shown in Figure 4.

Transportation of raw feed materials (Transportation 1) included the following conditions. Some raw materials in feed were not commonly produced, such as squid meal. Although Asian countries were the main producers, some South American countries such as Peru also produced squid meal. Additionally, Peru and Chile were the largest fishmeal producers, but the US produced a small portion of fishmeal. For the shrimp feed analysis, this study assumed that all the feed raw materials were manufactured locally (10km) except for the squid meal, which was assumed to be transported from South America (5200km).

Transportation of feed to the hatchery and farm (Transportation 2 and 3) was assumed to be from feed suppliers located in Texas. Diesel-trucks were used to transport feed from supplier to the hatchery and farm (50 km).

Transportation of PLs (Transportation 4) was from the hatchery to farm. Because the hatchery and farm were located at the same site, this transportation was negligible (assumed to be zero).

Transportation of salt (Transportation 5) was from the salt supplier to farm. Since the farm was very close to the coast, all of the water used in the farm was seawater (Transportation 7). No artificial seawater was created at the farm by mixing transported salt and freshwater, so the transportation of salt was zero.

Transportation of shrimp product (Transportation 6) was assumed to be from farm or retailer to consumer. As mentioned previously, the model farm was assumed to be located near the Gulf Coast in Texas. This study also assumed the farm or retailer sold shrimp to consumers located within 60km, with an average transportation distance of 25 km. Passenger vehicles were used in this process with an assumed average load of 1.57 passengers (U.S. Department of Transportation, 2001).

Transportation of seawater (Transportation 7) was assumed to be from the coast area to farm, because the farm was located in Texas in close proximity to the coast (4km). Impacts for seawater transportation from the coast to farm were assumed to be negligible.

Commercial transportation of the shrimp product (Transportation 8, 9 and 10, in Alternative 2 scenario only) was assumed to be between the farm, processing plant, wholesalers and retailers. Transportation distance from the farm to processing plant (Transportation 8) was 30 km. The distance from the processing plant to wholesalers was 300 km. The distance from the wholesalers to retailers was 75 km. Refrigerator-trucks were used for the commercial transportation process, which consume an additional 1.89 L of diesel fuel per hour compared to regular diesel trucks. The average speed of the refrigerated-truck was assumed to be 55 mile/hour. The transportation time was obtained by dividing the transportation distance by the average speed. The additional diesel consumption for maintaining the low temperature in the refrigerator-truck could then be calculated.

3.2 Life Cycle Energy Use

Shrimp farming required the most life cycle energy of any stage (95%, Figure 7) in the local market scenario (Alternative 1). The total life cycle energy for 1.8 kg of shrimp product for this scenario was 179 MJ, or 99 MJ/kg shrimp. In the shrimp farming stage, electricity consumption was the main contributor to energy use, while feed production and construction materials also played important roles (Figure 8). The energy intensities of various construction materials are listed in Appendix 4. The electricity requirements of equipment at the shrimp farm were 4.2 kWh/kg shrimp, mainly consumed by water pumps (59%), foam fractionator pumps (17%), and oxygen generators (24%) (Figure 9). Feed production energy was primarily distributed between fishmeal production (60%) and the feed manufacturing process (24.5%), while production of the other ingredients consumed only 15.4% of the energy (Figure 10). Moreover, energy intensity was 2.4 MJ/kg for crop ingredient production while it was 10.2 MJ/kg for fishmeal and fish oil production, which appears more energy intensive.

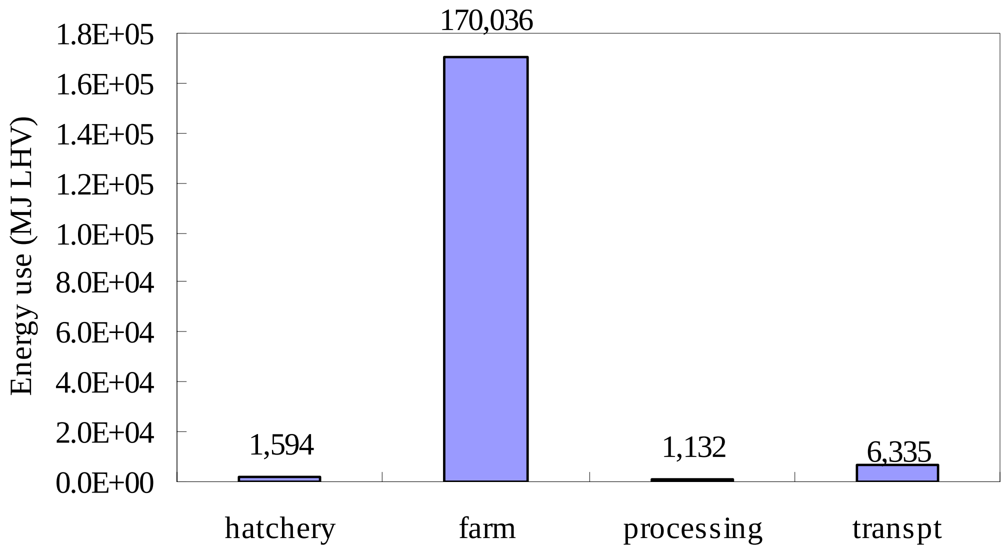


Figure 7 Contributions to energy use associated with the life cycle production and distribution of 1800 kg fresh shrimp produced in the US (Alternative 1 scenario).

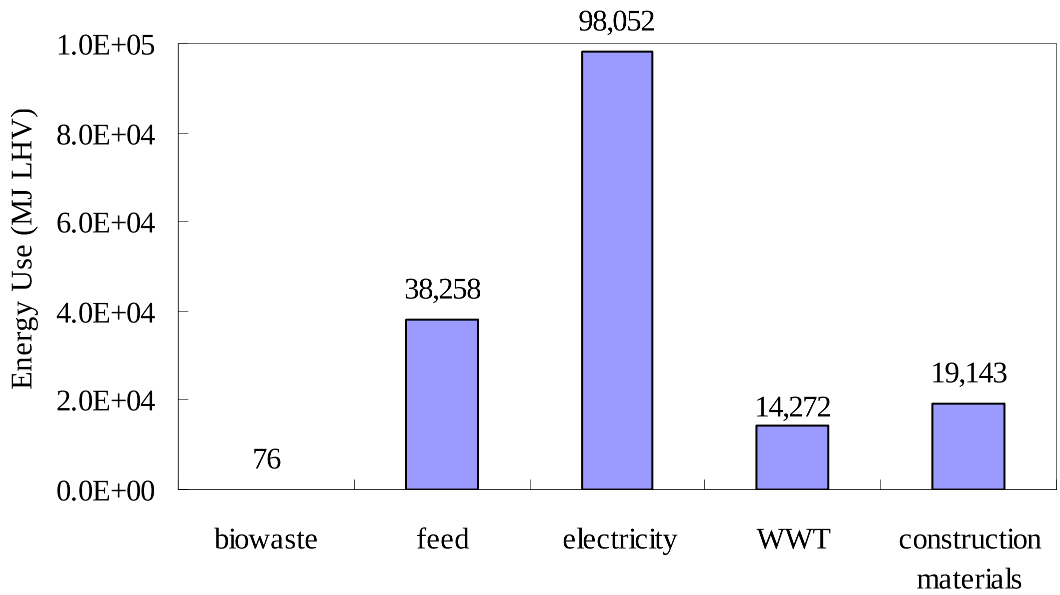


Figure 8 Contributions to energy use associated with the farming of 1800 kg fresh shrimp produced in the US (Alternative 1 scenario).

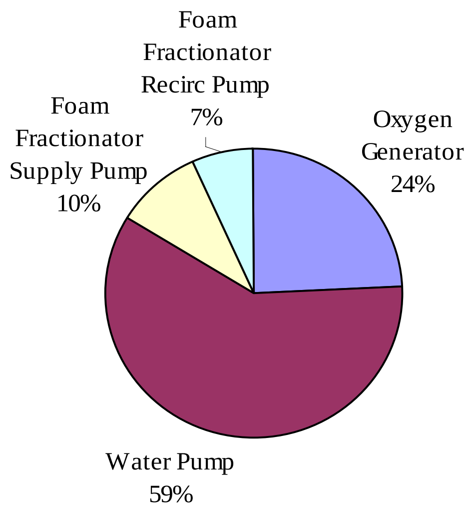


Figure 9 Electricity consumption for shrimp farming

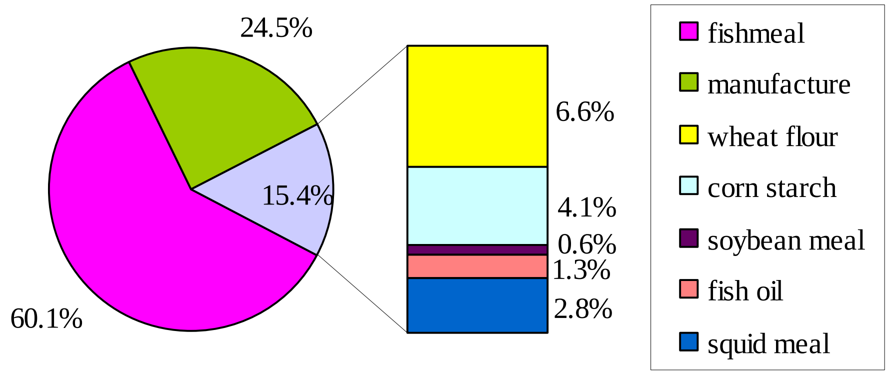


Figure 10 Energy consumption for feed raw material production

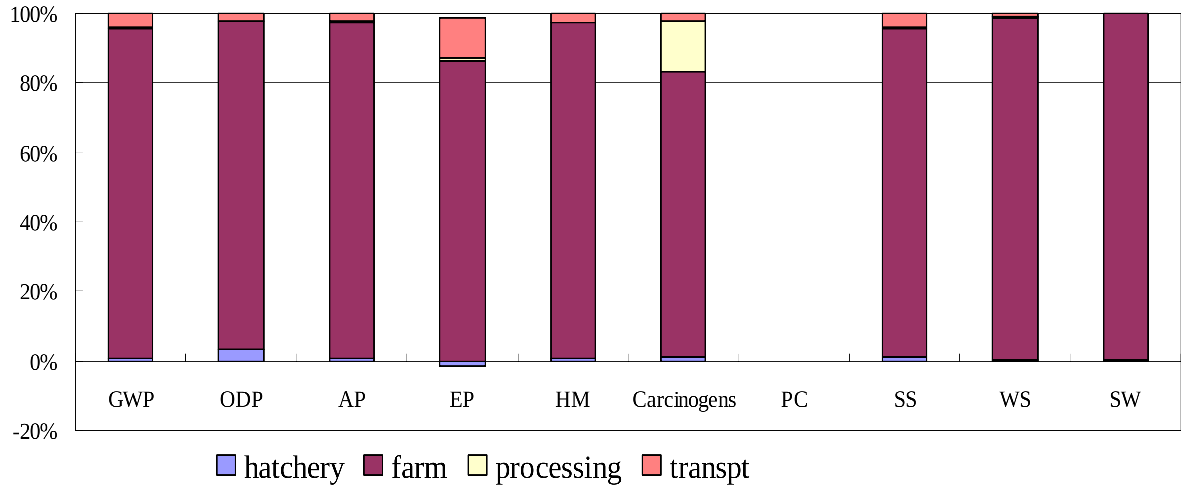
4 Life Cycle Impact Assessment Results

A life cycle assessment was carried out to explore the environmental impact created by each stage of the shrimp production system. Eco-indicator 95 was used as the impact assessment method to quantify: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), heavy metals (HM), carcinogens, pesticides (PC), summer smog (SS), winter smog (WS), and solid waste (SW). Simapro (Version 7) was utilized to obtain all background data on raw material production, energy generation, and waste disposal.

In terms of overall environmental impacts, shrimp farming was the dominant stage (Figure 11). Shrimp farming impacts came from use of shrimp feed, biosolids treatment, electricity generation, wastewater treatment, construction material production and shrimp metabolism. Electricity consumption was the largest contributor to global warming, acidification, eutrophication, carcinogen emission, heavy metal, winter smog and solid waste emission (Figure 12). As shown in Figure 10, water pumps were the largest user of electricity. Shrimp feed production also played an important role in ODP (Figure 12). The impacts of biosolid disposal in a landfill were negligible. Impacts of other biosolid handling alternatives are discussed in Section 5.4.

The impacts of feed production mainly arose from fishmeal production (Figure 13). As shown in the figure, the net eutrophication impact of fishmeal, fish oil and squid meal were negative, because the amount of phosphorus consumed by fish was more than the amount emitted during fish ingredient production.

Normalization was an optional step in life cycle impact assessment that was used to better understand the relative importance and magnitude of the impact category (Figure 14). Normalization calculates the magnitude of indicator results relative to reference information (ISO 14042 standards 2000E). In this study, the normalized score for a certain impact category was obtained by determining the ratio of the absolute environmental impact results and the respective European annual per capita impacts. The European annual per capita impacts are given in Appendix 5 (Goedkoop, 1995). As shown in the figure below, WS, GWP and AP were the most significant environmental impacts and farming was the main contributor.



GWP	ODP	AP	EP	HM
10,633 kg CO_2	0.003 kg CFC-11	91.1 kg SO_2	2.7 kg PO_4	0.028 kg Pb
Carcinogens	**PC**	**SS**	**WS**	**SW**
0.00019 kg B(a)P	0.0 kg act.subst	5.3 kg C_2H_4	93 kg SPM	1,129 kg

Figure 11 Contributions to each impact category associated with the life cycle production and distribution of 1800 kg of fresh shrimp produced in the US (local scale scenario)

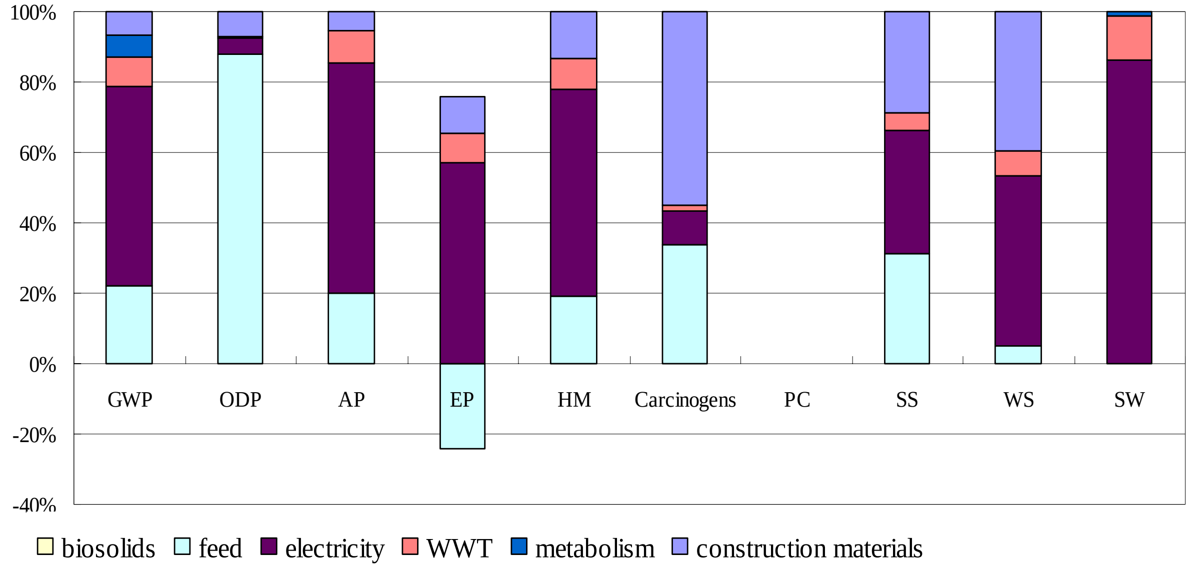


Figure 12 Contributions of major inputs and outputs to impacts associated with producing 1800kg of fresh shrimp

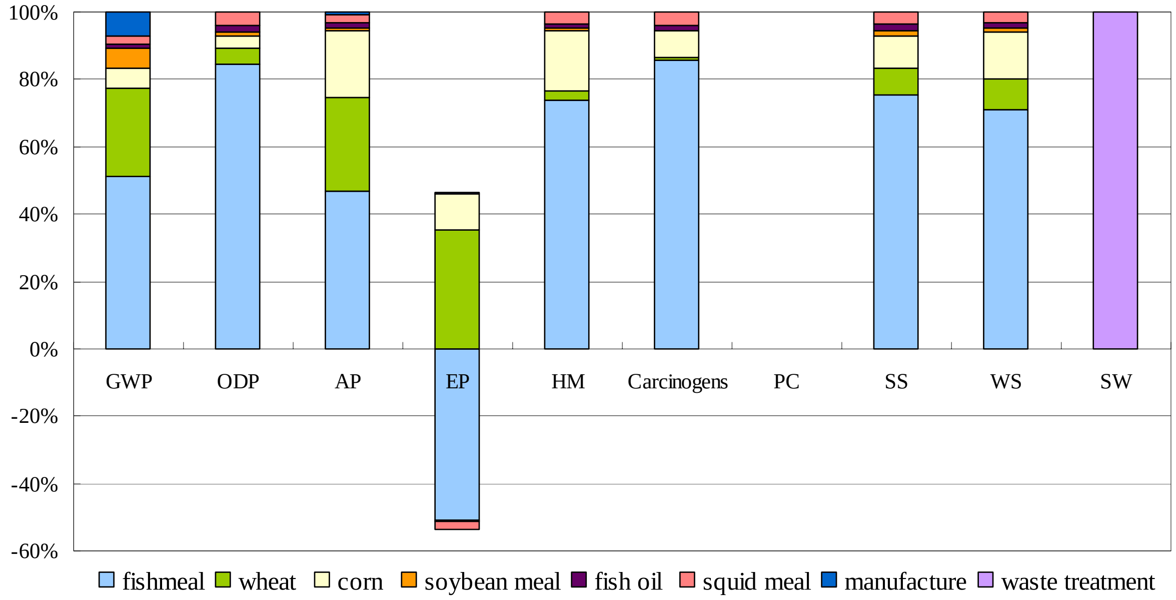


Figure 13 Contributions of each feed component to impacts associated with shrimp feed production needed to grow 1800kg of shrimp

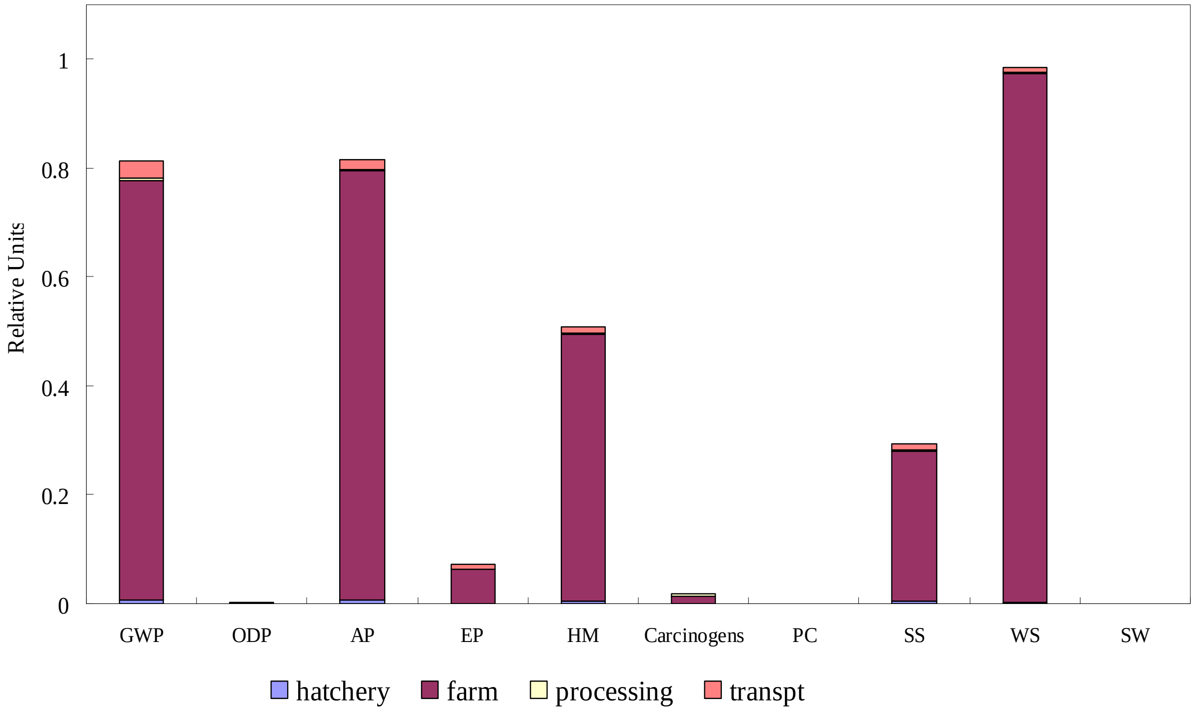


Figure 14 Normalised LCA results for 1800 kg of fresh shrimp production and distribution in the US (Alternative 1 scenario)

5 Scenario Analysis

5.1 Transportation Scenario Analysis

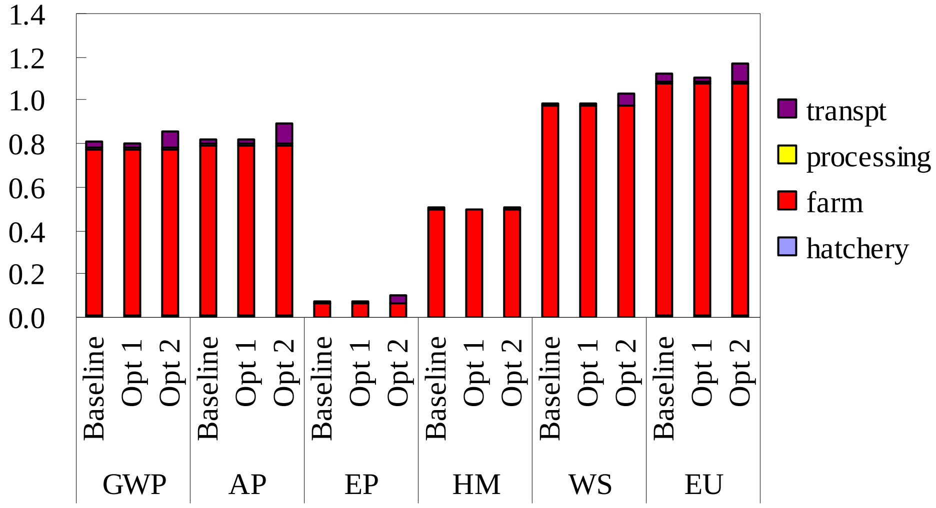
Baseline was a local-scale scenario, which included the transportation of feed to farm and hatchery, PLs to farm, and the shrimp product to consumer (Transportation 1-6). In this section a scenario analysis was conducted to determine the relative significance of each transportation stage (Transportation 1-6). A scenario analysis of marketing scale is conducted in Section 5.3, which includes the analysis of shrimp commercial distribution (Transportation 8-10). The following two scenarios were analyzed in this section:

Option 1: local scale; distance was 300 km; by truck

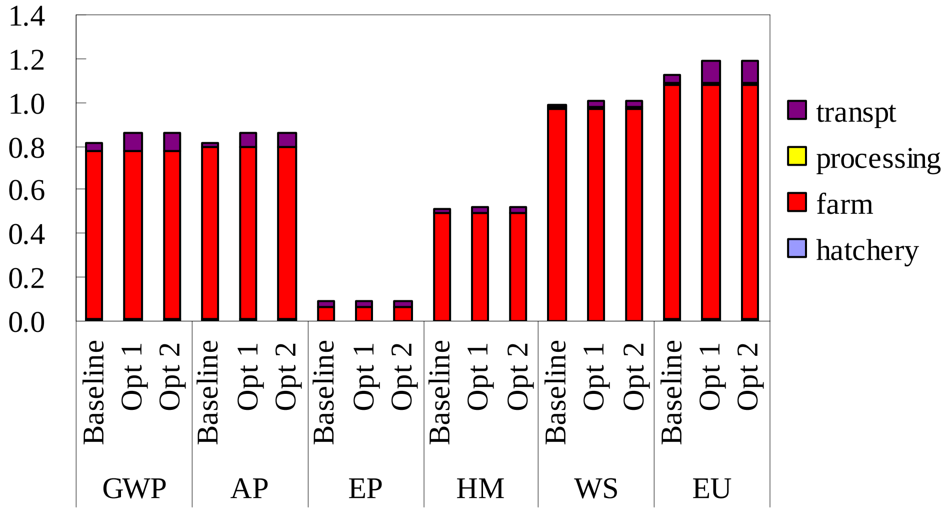
Option 2: regional scale; distance was 1500 km; by truck

For example, in the scenario analysis of Transportation 1 (Figure 15, a), when Option 1 was chosen, the transportation from feed material suppliers to feed mill (Transportation 1) was 300 km by truck while all other stages of transportation remained the same as the baseline. The baseline conditions were described in Section 2.

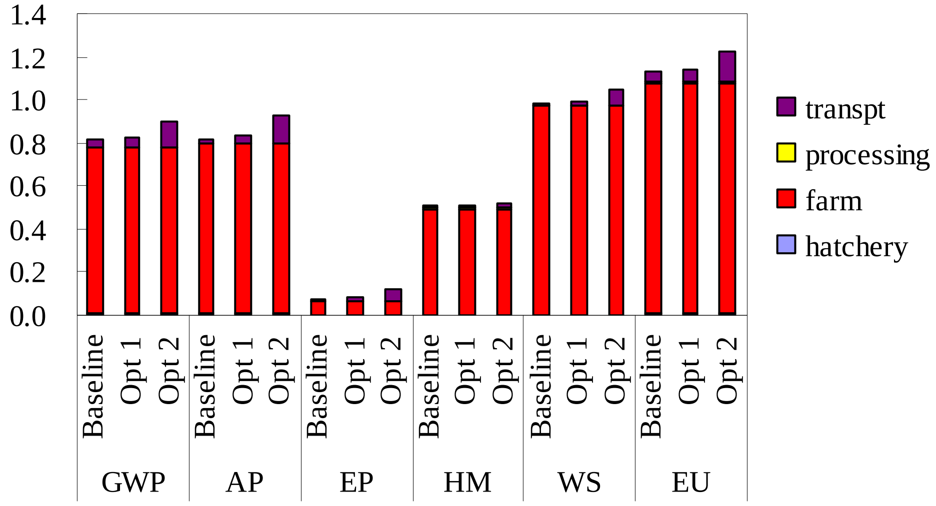
The impact categories in the scenario analysis were global warming, acidification, eutrophication, heavy metal, winter smog and energy use. According to the normalized impacts, WS and EU were the highest impact categories (Figure 15). The impacts of transporting feed raw materials (Transport 1), shrimp feed to farm (Transport 3) and shrimp product to consumer (Transport 6) were noticeably different, but small, when comparing the two scenario options (Figure 15, a, c, e). The impacts of transporting feed to the hatchery and PLs to the farm showed almost no difference between the two scenarios (Figure 15, b, d). Since the consumption of feed at the hatchery and PLs at the farm was very small, the transportation of the small amount of feed and PLs had little impact on the system as a whole. Distribution of each transportation stage to total transportation impacts is shown in Appendix 7.



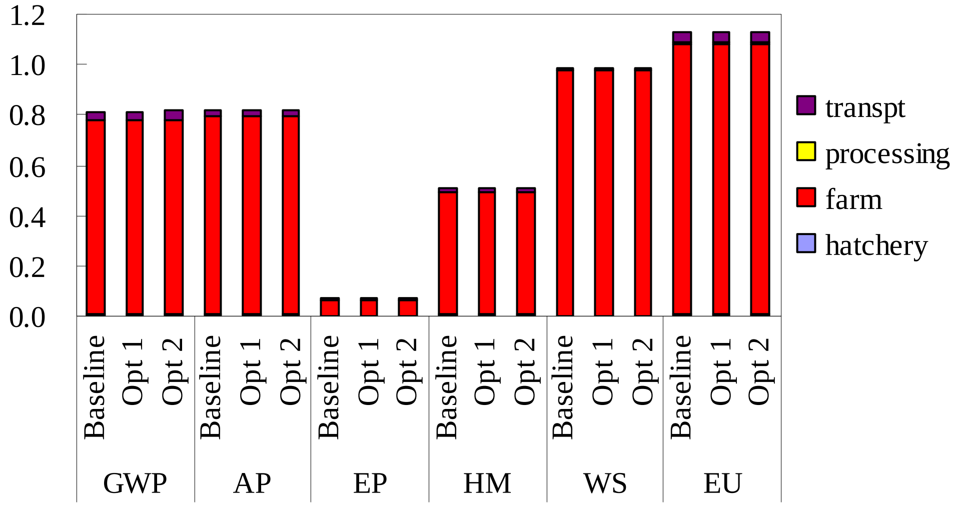
a) from feed raw material suppliers to feed mill (Transportation 1)



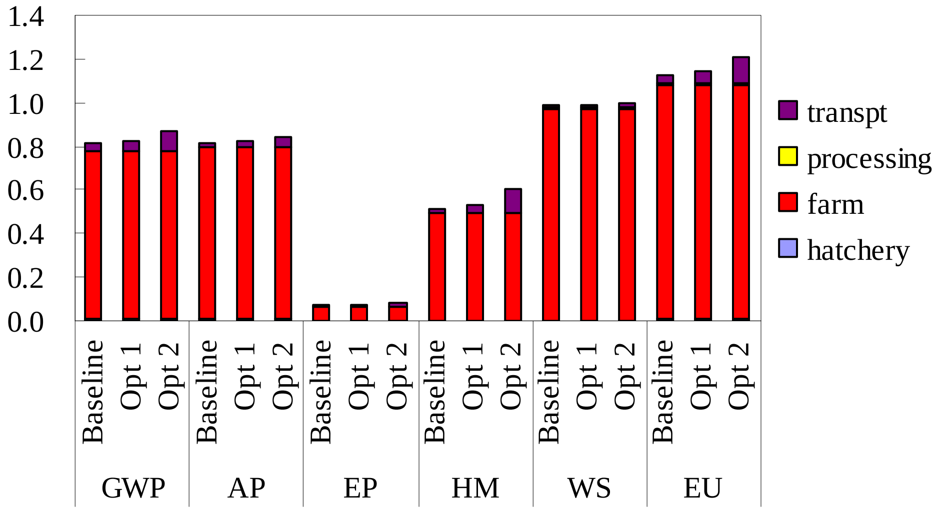
b) from feed mill to hatchery (Transportation 2)



c) from feed mill to farm (Transportation 3)



d) from hatchery to farm (Transportation 4)



e) from farm to consumer (Transportation 6)

Figure 15 Normalised LCA results for 1800 kg of fresh shrimp production and distribution in the US (Alternative 1 scenario) for (a) Transportation 1, (b) Transportation 2, (c) Transportation 3, (d) Transportation 4 and (e) Transportation 6 scenario analysis.

5.2 Marketing Scale Scenario Analysis

The flow chart presented in Figure 4 shows both commercial alternatives: Alternative 1 (Transport 1-4, 6) and Alternative 2 (Transport 1-4, 6-10). Both scenarios had the hatchery, farm, and shrimp feed stages in common. The differences between the two alternatives were product processing, storage and transportation activities. For local-scale marketing (Alternative 1), shrimp would be sold directly to local consumers at shrimp farms in Texas. The main activities in this process were product chilling and transporting the product 25 km from the farm to consumers. In a national-scale marketing scenario (Alternative 2), shrimp was sold to consumers in Michigan. In this scenario, it was assumed that the farm, processing plant, and wholesalers were located in Texas while retailers and consumers were located in Michigan. The shrimp was pre-frozen at the farm or processing plant. Frozen shrimp was then transported to wholesalers and retailers by refrigerated-truck. The frozen shrimp was stored in freezers at wholesalers for 30 days and retailers for 10 days. The transportation distance was 30 km from farm to processing plant (Transport 8), 300 km from processing plant to wholesalers (Transport 9), 2190 km from wholesalers to retailers (Transport 10), and 25 km from retailers to consumers (Transport 6).

The scale of marketing had a large impact on life cycle energy usage and environmental impacts. Energy consumption and environmental impacts in the national scale scenario (Alternative 2) were almost 1-2 times that of the local-scale scenario (Alternative 1) (Figure 16). This was due to longer transportation distances using refrigerated trucks, which consume more diesel than regular trucks for temperature control. More electricity was consumed for shrimp freezing and cold storage in the national-scale scenario than the local-scale scenario which involved only shrimp chilling.

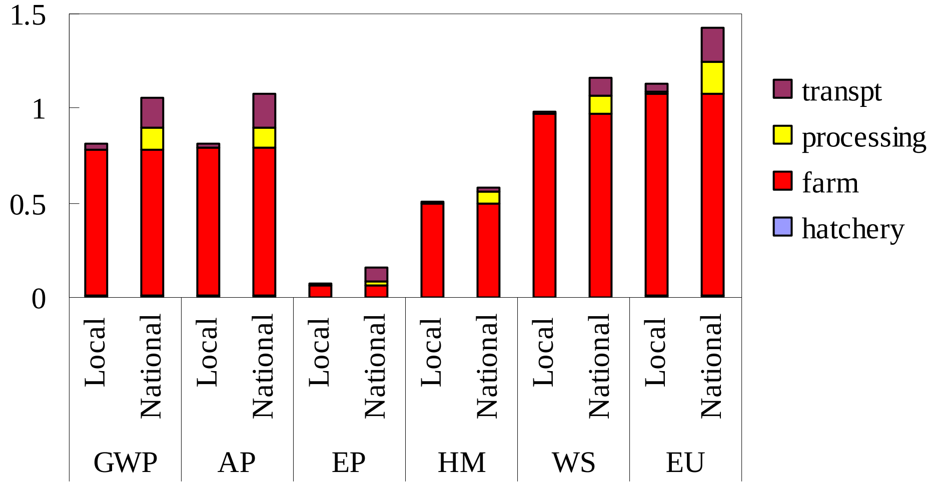


Figure 16 Normalised LCA results for 1800 kg of fresh shrimp production and distribution in the US for marketing scale scenario analysis (Alternative 1 is local-scale marketing and Alternative 2 is national-scale marketing).

5.3 Farm Location Scenario Analysis

In the baseline case (local-scale marketing scenario, described in Section 2), the model farm was located near the Gulf Coast in Texas and all of the water used in the farm was seawater. When the farm was located further away from the coast, a portion of water used in the system was assumed to be made by mixing salt and freshwater while the remainder would be trucked from the sea. Therefore, salt and freshwater consumption and transportation were modeled in the farming process when farms were not close to the coastal area. To evaluate the impact of the farm location, 3 scenarios were developed based on the proximity of the farm to the coast. Transportation of salt from supplier to the farm was assumed to be 30km by truck in the 3 scenarios. The 4th scenario was developed to evaluate the impact of a farm located in Hawaii compared to mainland farms. The 4 scenarios were:

Option 1: farm was close to the coast (10km); 25% of total water used by the farm was artificial water and 75% was seawater; seawater was trucked from the coast

Option 2: farm was moderately far from the coast (50km); 50% of total water used in the farm was artificial water and 50% was seawater; the seawater was trucked from the coast

Option 3: inland farm, located in Michigan; 100% of water used in the farm was artificial seawater

Option 4: farm was located on the coast in Hawaii. At this farm 100% seawater was used, and feed was transported from Texas by barge (around 6260 km from Texas to Hawaii). Road transportation from the feed supplier to the port in Texas, and from the port to farm in Hawaii represented small distances, so were neglected. As a whole, the only difference between Option 4 and the baseline was transportation of feed from supplier to farm and hatchery.

Option 1, 2 and 3 consumed more energy and generated more GHG (GWP), SO_2 equivalent (AP) and PO_4 equivalent (EP) impacts than the baseline system (Figure 17). This was caused by the long distance transport of seawater, and consumption of salt and freshwater for making artificial seawater. It indicates that the impacts of long distance seawater trucking from a coastal area traded off against impacts with making artificial seawater at the farm. The impacts of Option 1 were lower than Option 3 (Figure 17); when the farm was located close enough to the coastal area (i.e. Option 1) trucking some seawater was a better choice. However, closer proximity of the farm to the coast did not necessarily improve environmental performance. For example, Option 2 (shorter trucking distance with a larger portion of seawater) produced much higher impacts than Option 3 (Figure 17). It indicated that when the farm was located far from the coast (i.e. Option 3), making artificial seawater was preferable in terms of energy use and environmental impacts. On the other hand, compared to a farm located on the mainland coast (baseline), a farm in Hawaii (Option 4) resulted in 40-338% higher environmental impacts due to longer distance transport of feed from the mainland to Hawaii (Figure 17).

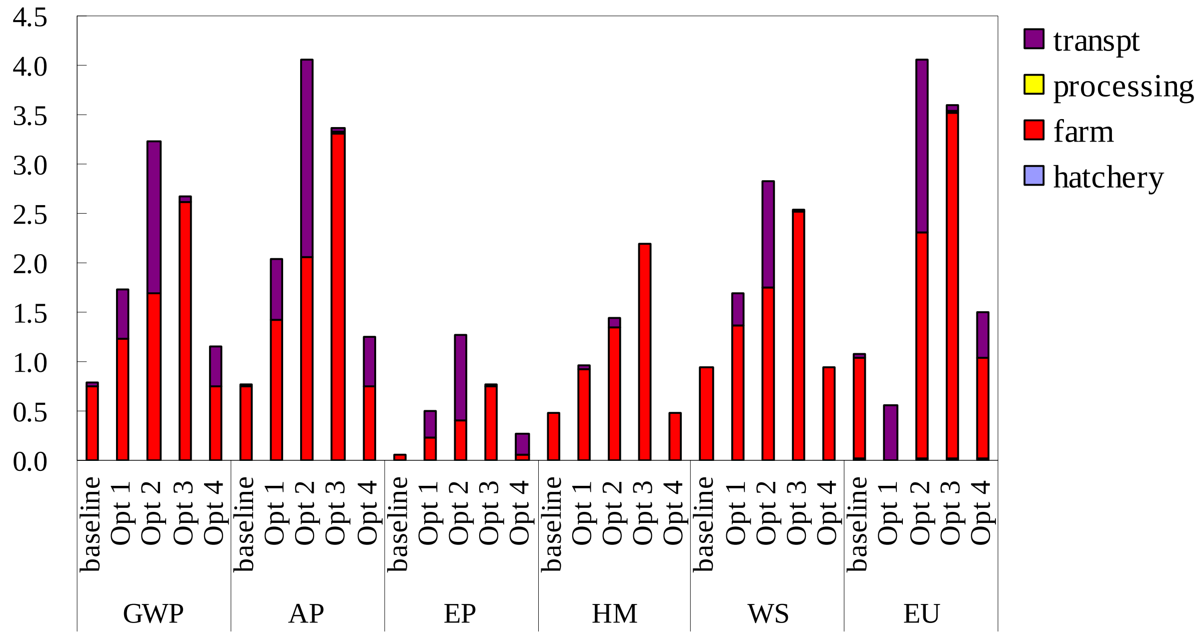


Figure 17 Normalised LCA results for 1800 kg of fresh shrimp production and distribution in the US for farm location scenario analysis.

To further investigate the environmental impacts of farm location when the shrimp consumer is in Michigan, two scenarios were compared. Scenario 1 was the national-scale scenario (Alternative 2), in which shrimp was cultured in the RAS coastal farm in Texas, then frozen and transported to Michigan to be sold. In Scenario 2, the farm was an inland farm located in Michigan. Fresh shrimp was sold from the farm directly to local consumers in Michigan. Figure 18 presents the life cycle results of these two scenarios. The impacts of shrimp culture (farming only) in Michigan (Scenario 2) were 2.6-12 times those in Texas (Scenario 1). This was due to a large amount of salt consumed at the Michigan inland farm for making artificial seawater, which increased the energy consumption and impacts in farming. However, the impacts of processing and transporting frozen shrimp cultured in Texas (Scenario 1) were 5-7 times greater than those of local distribution in Michigan (Scenario 2). Overall, Scenario 2, with the local inland farm and local distribution, produced 152-392% higher impacts. The results did not include the impacts of the energy required to heat the Michigan shrimp farm. If the heating parameter was included, the energy use and environmental impacts of culturing shrimp in Michigan would be even higher. This result provides evidence that it was better to buy shrimp produced on Southern US coast than culture shrimp locally in Michigan, in terms of energy use and environmental impacts.

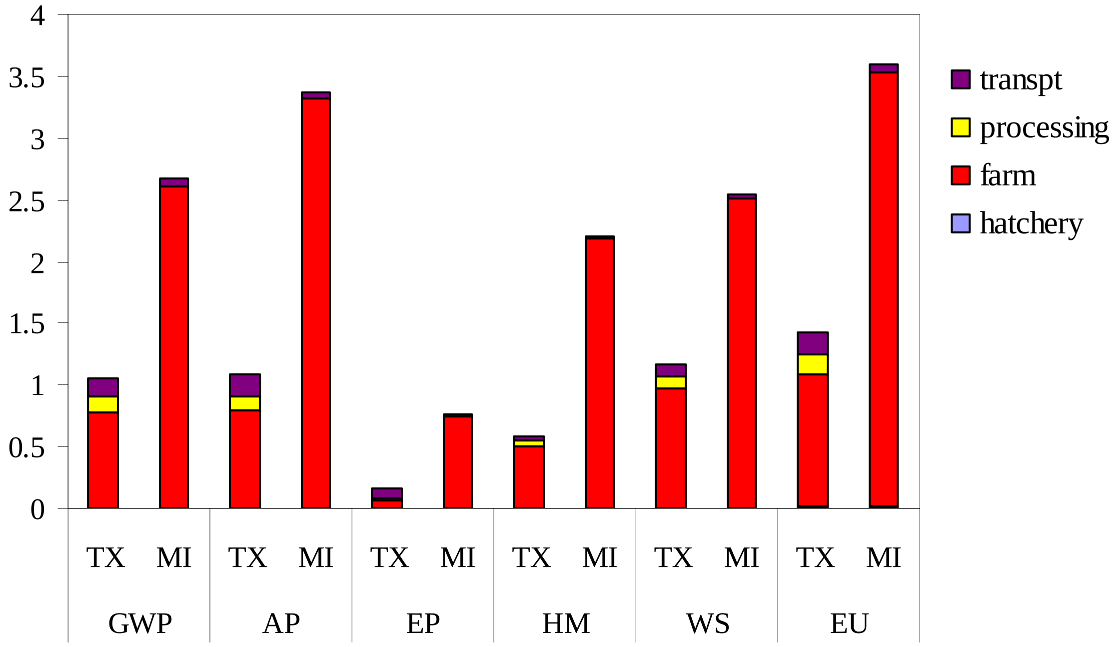


Figure 18 Normalised LCA results for 1800 kg of shrimp production in 1) Michigan and 2) Texas and shrimp distribution toMichigan

5.4 Biosolids Treatment Scenario Analysis

Scenario analysis based on Houillon and Jolliet (2005) was conducted on the impacts of six biosolids treatment methods: spreading of limed pasty sludge on agricultural land (AGRI), incineration of pasty sludge in a fluidised bed (INCI), wet oxidation of liquid sludge (WETOX), pyrolysis of dried sludge (PYRO), incineration in cement kilns of dried sludge (CEME), and landfilling of limed pasty sludge (LANDF). Electricity and natural gas consumption for sludge treatment and heating were analyzed in the six treatment alternatives. Energy generation from the treatment processes was also taken into account. For example, in fluidized bed incineration, heat was recovered from the flue gas, which enabled natural gas savings. Based on the Houillon and Jolliet (2005) study, incineration in fluidized beds and agricultural spreading were the most attractive processes from an energy perspective, while incineration in cement kilns had the best global warming balance. Although the six sludge treatment scenarios used different techniques, they did not make significant differences in the life cycle results (Figure 19). Saline sludge discharged from the RAS farm contains large amounts of salt. Due to limited information about saline sludge treatment, treatment of municipal waste sludge was analyzed in this study. To treat saline sludge and water, a desalination process will be needed and extra material and electricity consumption may also be required.

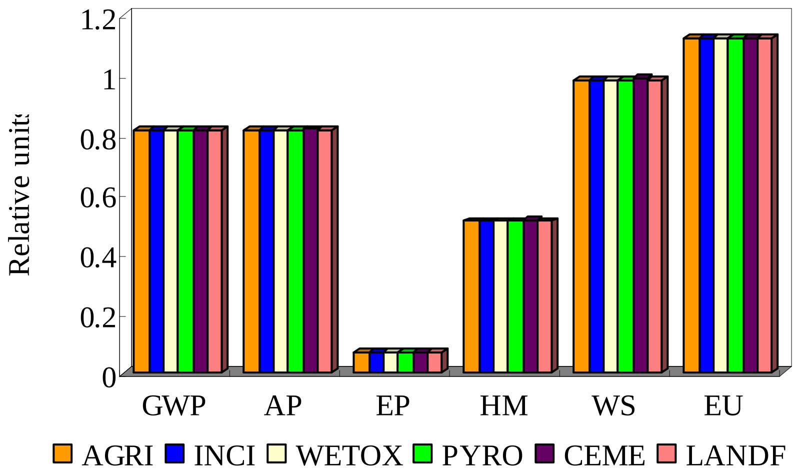


Figure 19 Normalised LCA results for 1800 kg of fresh shrimp produced in the US (Alternative 1 scenario) for biosolids treatment methods scenario analysis.

6 Comparison with Conventional Shrimp Aquaculture

The LCA of frozen shrimp produced in Thailand was modeled by Mungkung (2005). This section compares the environmental performance of shrimp production in the RAS and conventional flow-through culture systems. The life cycle performance of shrimp production and distribution were also compared. Mungkung (2005) used CML 2000 as her analysis method, and used 1.8kg of shrimp as a functional unit. To make the results comparable, the same analysis method and functional unit were used for RAS in this section, for this comparison only. The environmental impact categories assessed include AP, EP, GWP and ODP.

6.1 Shrimp Culture System Comparison

This assessment considered water consumption, electricity use, and environmental impacts attributed to the RAS and conventional culture systems to compare their performance for the farming stage only. As expected, the recirculating system used much less water than the conventional aquaculture system because RAS realized water reuse by using a water treatment system onsite. For 1.8 kg shrimp production, water consumption in the Thailand conventional farm was 12.3m^3, or 6.8m^3/kg shrimp (Mungkung, 2005). Inventory analysis of the US farm indicated that water consumption for 1.8 kg shrimp production at the RAS farm was 3.8 m^3, or 2.1m^3/kg shrimp – just 31% of the water used by the conventional farming system.

While RAS was better regarding water savings, it was not as energy efficient as the conventional aquaculture system. Energy consumption for 1.8 kg of shrimp production at the Thailand conventional farm was 5.4 kWh, or 3kWh/kg shrimp (Mungkung, 2005). The energy consumption for 1.8 kg shrimp production for the RAS farm was 7.8 kWh, or 4.3 kWh/kg shrimp – 1.4 times that of the conventional shrimp farm. Operation of RAS required more electricity for water recirculation and treatment in the system.

As shown in Figure 20, EP for the conventional farm was 1.4 times greater than that of the RAS farm, due to the impacts of wastewater treatment for the conventional farm. The GWP was also higher for the conventional farm than for the RAS farm, because of the usage of burnt lime. On the other hand, the conventional farm produced a lower AP impact than the RAS farm.

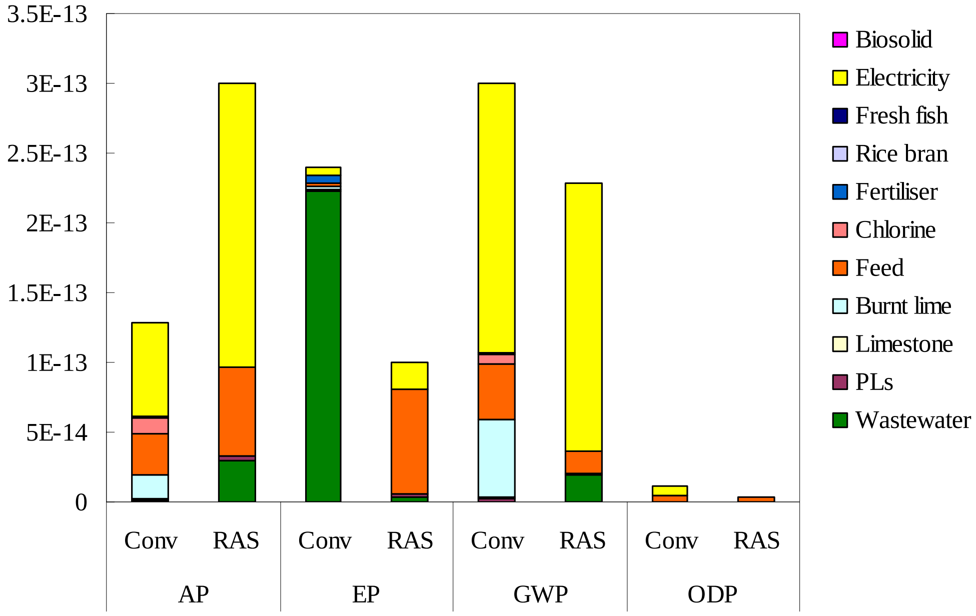


Figure 20 Normalized LCA results for 1.8 kg of shrimp produced in a conventional flow-through culture system and RAS

6.2 Total Life Cycle Comparison

The life cycle impacts of 1.8 kg of fresh shrimp cultured in a conventional farm and in a RAS farm were compared. These two farms were both assumed to be located at the coastal site in Texas and use local-scale distribution model. The local-scale marketing scenario was described in Section 3.1.3. Overall, the only difference between these two scenarios was the farming stage.

The conventional flow-through farm in Thailand (assumed to exist in Texas) used an intensive farming system coupled with an environmental management system, following the Code of Conduct guidelines developed by the Department of Fisheries in Thailand (Mungkung, 2005). The RAS farm was described in Section 2.2 and Section 3.1.2.

The conventional flow-through farm scenario produced higher impacts of EP, GWP and ODP, but a lower AP impact (Figure 21). The life cycle comparison results were similar to the farming stage comparison (Figure 20), which isn't surprising because shrimp culture was a dominant stage in the life cycle system.

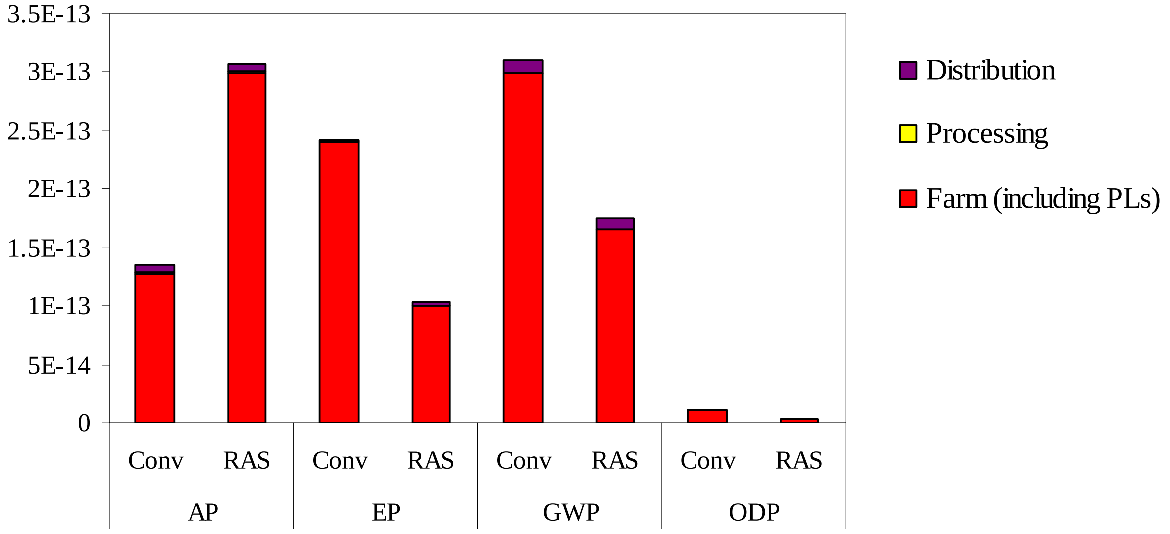


Figure 21 Normalized LCA results for 1.8 kg of fresh shrimp produced in conventional farm and RAS farm in the US

An environmental performance comparison was also made between shrimp production by RAS in the US and shrimp production by the conventional farming system in Thailand. The US scenario was the baseline (Alternative 1, local-scale scenario) analyzed in Section 4 in this study. On the other hand, the Thailand scenario was an international-scale system. The shrimp produced in Thailand were imported to the US for sale. Transport of the shrimp product from Thailand to the US (14,630 km by container ship) was included in the assessment. For the Thailand system, the PL rearing at Chacheongsao hatchery, shrimp culturing at a Thailand farm, product processing, and storage were described in Mungkung (2005).

Production and sale of shrimp in the US generated 15-82% lower AP, EP, GWP and ODP impacts than production of shrimp in Thailand and subsequent transport to and consumption in the US.(Figure 22). The results indicated that culturing shrimp by RAS locally in the US was preferable than importing shrimp from a conventional farm in Asia.

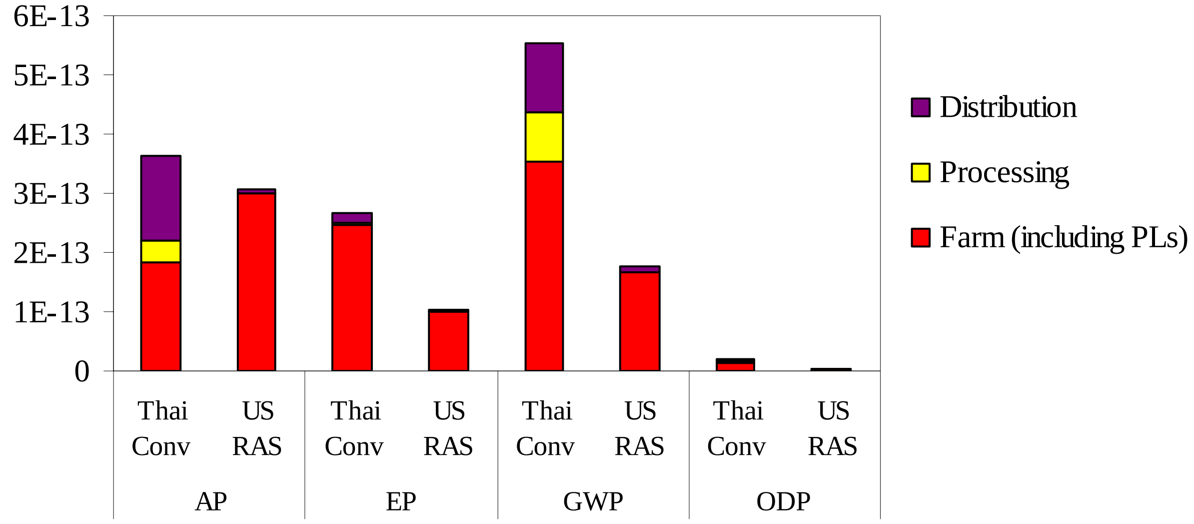


Figure 22 Normalized LCA results for frozen shrimp produced in Thailand, fresh shrimp

7 Conclusion

This study evaluated the environmental and energy performance associated with shrimp produced by a recirculating culture system in the US. LCA results revealed that shrimp farming contributed the most to the energy use and environmental impacts in the life cycle system. The energy demand and pollutant emissions in farming mainly came from electricity consumption: electricity use represented 58% of energy use and produced 4-86 % of environmental impacts. The use of shrimp feed accounted for 23% of energy use and 5-88% of environmental impacts in farming. In feed production, fishmeal was an important ingredient in terms of energy use and environmental impacts.

Normalization was used to assess the relative significance of different impact categories to a chosen baseline. This analysis suggested that global warming, acidification and winter smog were three important impact categories. The normalized score for a certain impact category was obtained by determining the ratio of the category indicator result of the product and that of a reference. In this study, European annual per capita impacts were used as the reference. However, with a different reference case (i.e. annual per capita in the US), the normalized score of each impact category could change significantly.

The study provided a basis for comparison with other aquaculture systems. It revealed that water used by a RAS was 31% of that by a flow-through system. On the other hand, electricity usage by the RAS was 1.4 times that of the flow-through system, because operation of the RAS required more electricity for water recirculation and treatment in the system. The results confirmed the expectation that total water usage was reduced and the energy requirement increased at the RAS farm. From an environmental impact perspective, the RAS produced lower GWP, EP, and ODP impacts while the conventional farm showed better performance in terms of AP. There was a trade-off between energy consumption, water use and environmental impacts. It is difficult to conclude, in general, which culture technique is better. The choice depends on the importance of individual impacts, or a subjectively weighted aggregate environmental impact score, which was not calculated in this study.

A scenario analysis was also conducted to examine transportation, farm location, biosolids treatment and marketing. Generally speaking, a smaller marketing scale generated lower impacts because of energy savings in product transportation and storage. Impacts of the local-scale scenario were just 42-87% of those in the national-scale scenario.

Farm location was also an important factor. There was a trade-off between trucking seawater and making artificial seawater locally. The energy use and environmental impacts in mainland coastal farms were 30% and 9-37% of those in inland farms, respectively. It was recommended that with the same culture technique and product distribution, coastal farms were preferable to inland farms in terms of energy savings and pollution reduction.

When the shrimp consumer is in Michigan, buying shrimp from the Southern coast saved 70% energy and reduced 86-643% pollutant emissions, compared to culturing shrimp locally in Michigan. The results did not include the impacts of the energy required to heat the Michigan shrimp farm. If the heating parameter was included, the energy use and environmental impacts of culturing shrimp in Michigan would be even higher. Moreover, for American consumers, producing shrimp by RAS in this country was recommended, compared to importing shrimp from Asia. Shrimp production and distribution in the US resulted in a 15-82% reduction in pollutant emissions.

The LCA results were based on a scale-up of a research scale recirculating farm and included a wide range of assumptions. When design parameters could not be obtained from the Oceanic Institute, in the design of the recirculating aquaculture system, they were based on literature data. For example, I assumed that the service life of construction materials in the farm was 25 years. These assumptions may affect the accuracy of the LCA results. In addition, several assumptions were made to model transportation and facility location. For example, transportation from farm to consumer was assumed to be 30km by passenger vehicle. It was also assumed that the farm and hatchery were located on the coast in Texas. Different locations for the farm and hatchery lead to changes in the impacts of raw material transportation. Due to these assumptions and uncertainties, a scenario analysis was conducted to determine the impacts of alternatives to the transportation, farm location, marketing scale and biosolids handling baseline assumptions. Results revealed that farm location and marketing scale were important to the system, while transportation and biosolids handling were not significant factors.

Disease issues were not analyzed in this study. RAS was located in a closed building and the system had little air and water exchange with the outdoor environment, so disease may not be a significant problem. This issue should be considered in further evaluation of RAS.

In future research, analysis of commercial-scale recirculating shrimp farms should be conducted. Moreover, considering the significance of electricity consumption in the farm stage, future studies could also focus on new strategies for energy saving at the farm (e.g., the water pumps at the farm). To improve the energy performance in the RAS operation, use of renewable energy is a possible solution. In addition, the opportunity to reduce the water replacement rate for the RAS should be investigated. 10% water replacement based on Oceanic Institute led to large impacts for a RAS farm in Michigan, due to the impacts associated with a large quantity of salt replacement. General conclusions could not be drawn in terms of energy use and pollutant emissions for all sizes of recirculating shrimp farms. Sensitivity analysis of farm size would be required, and was not performed in this study. Finally, this LCA focused on environmental issues, which should be balanced against economic cost. Due to limited information, life cycle cost analysis was not conducted in this study.

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9 Appendix

Appendix 1 Shrimp aquaculture system survey for life cycle assessment (LCA)

Survey Introduction

Thank you very much for participating in this research project, Life Cycle Assessment of Sustainable Shrimp Aquaculture. The research is conducted by the School of Natural Resources and Environment and College of Engineering at University of Michigan. The major objectives of this study are to conduct life cycle analysis (LCA) and life cycle cost analysis (LCCA) to evaluate the environmental, energy and economic performances of zero-exchange, re-circulating indoor aquaculture systems. In addition, we will compare these results with outdoor conventional aquaculture system to determinate the potential improvement of your system. By participating in this research, you will provide you with the material/energy consumption, environmental impacts and economic profile of your system and highlight opportunities for improvement. The raw data and information of individual farms will not be presented in the future published document; we will only present the life cycle analysis results and recommendations (the paper *Potential and Limitation of Life Cycle Assessment in Setting Ecolabelling Criteria by Mungkung et al.* will help you to have a better idea what information will be presented in the published documents). Figure 1 shows the life cycle stages of the shrimp aquaculture system and will help you to have a better idea of the question organization in this survey. (Note: if the data you have are different units than requested in this survey, please provide your data and unit and we will perform the unit conversion.)

The principle investigator (PI) of the research is Professor James Diana jimd@umich.edu. If you have any questions about this survey or want us to go over all the survey questions, please contact Wenting Sun swenting@umich.edu, 734-846-2862.

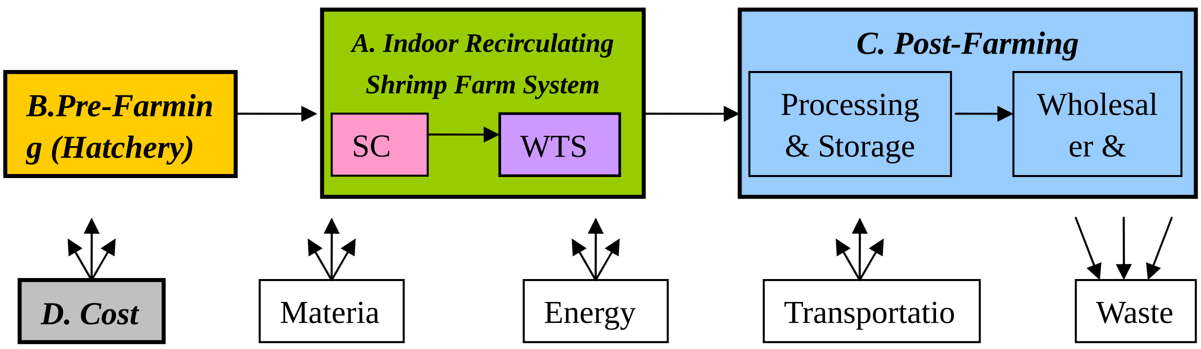


Figure 1. Life cycle stages of shrimp aquaculture system

General Information

Interviewer Name: ____________________________ Interview Date: ______________________________

Contact (email/telephone): ____

Do you want us to put your farm's name in the acknowledgements of this research? ☐ Yes ☐ No

A.Indoor Recirculating Shrimp Farming System

1. General Information

Location of shrimp farming system (City/State/Zip code): ____

Name of the organization that manages the system: ____

Expected service time of your system: _______years

Number of employees working in the farming system: ____________employees

2. Shrimp Culture System (SCS)

Please write a paragraph and sketch a process flow diagram to describe your shrimp aquaculture system. In the description paragraph and flow diagram, please indicate basic information and significant features/parameters about the aquaculture system. The following questions may give you some guidance.

Number of shrimp culture tanks: _______; size of each tank: _________ $feet^3$ or m^3 or gallon

Shrimp culture system land cover (exclude offices): ___________ $feet^2$ or acres

How long is one culture cycle (from post-larva to harvest)? ____ months/cycle

Number of culture cycles per year: __________cycles/year

Shrimp aquaculture system description:

Process flow diagram of the Shrimp Culture System

2.1 Material Consumption

2.1.1. Feed

Feed composition:

a. Commercial pelleted feed: ____ (brand)

Feeding rate: ________ lb/tank/week (month); feed price: ________$/lb (kg)

Feed supplier location (City/State/Zip code)____________________________________

Transportation from suppliers to shrimp farming system:

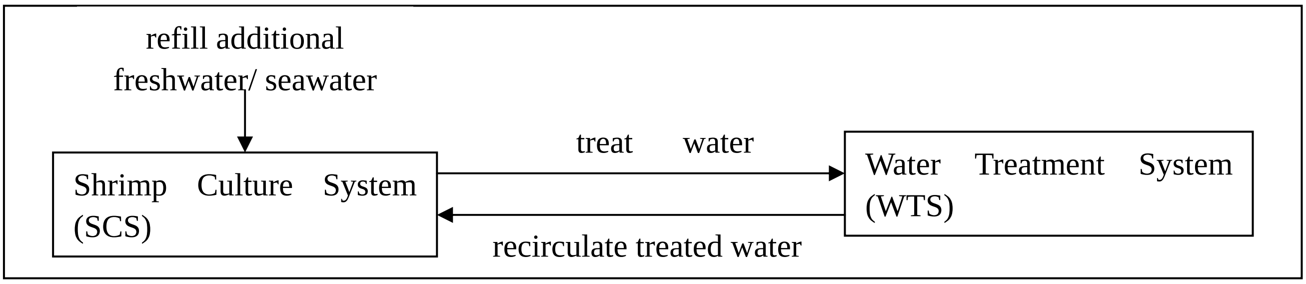
Vehicle type: ☐ Airplane ☐ Truck w/o Refrigerator ☐ Truck w/ Refrigerator
Vehicle load: _______ lb (kg) feed /vehicle

b. Any supplement added

Feeding rate: ________ lb/tank/week (month)

Ingredient (i.e. corn, husk)	Weight percentage (%) (ingredient weight/feed weight)	Ingredient weight (lb)	Price ($/lb)

2.1.2 Water



Water flow chart in recirculating shrimp farm system

Water source percentage: _______ % freshwater; _______ % seawater
Price: freshwater________$/1000 gallon; seawater________$/1000 gallons
Water volume in Shrimp Culture System V1: __________gallons
Water volume in Water Treatment System V2: __________gallons
Volume of water flow through treatment system Q1: __________gallons/day (week or month)
Volume of additional water refilled Q2: __________ gallons/day (week or month)
Seawater supplier location (City/State/Zip code)_____________________________________
Transportation from seawater supplier to shrimp farming system:
Vehicle type: ☐ Airplane ☐ Truck w/o Refrigerator ☐ Truck w/ Refrigerator
Vehicle load: ______________ gallon seawater/vehicle

2.1.3. Salt (If system uses freshwater, salt is needed.)
Salt-water rate: _______ lb salt/gallon freshwater; salt consumption: ________ lb salt/ week (month)
Salt price: ________$/lb (kg)
Salt supplier location(City/State/Zip code)_____________________________________
Transportation from salt supplier to shrimp farming system:
Vehicle type (i.e. UPS delivery truck):_____________________________________
Vehicle load: _______ lb (kg) salt /vehicle

2.1.4 Post-Larvae
Breed of post-larvae: ☐ white shrimp ☐ tiger shrimp ☐ Other: _______________
Post-larvae price: ________$/lb (kg)
Density of post-larvae in shrimp aquaculture system:
________lb /tank/cycle or ________(amount)/m^2 (m^3) or ________(amount)/tank/cycle

2.1.5 Other Inputs for Shrimp Culture System

Burnt lime: ___________kg (lb)/tank/week (month); Price_________$/ kg (lb)

Limestone: ___________kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

Probiotic substance (i.e. bacteria, yeast):

a. type ______________ ; ______kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

b. type ______________ ; ______kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

Micro-organisms (i.e. algae):

a. type _____________ ; ________kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

b. type ____________; ________ kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

Other main input:

a. name: ____________ ; _______kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

b. name: ___________; ________kg (lb)/tank/week (month) ; Price_________$/ kg (lb)

2.2 Shrimp production

Weight of shrimp production per cycle _________________ lb (kg)/tank/cycle

Number of shrimp per lb: _____________(amount)/ lb

If the shrimp product meets any food standard/certification, list here: __________________________

2.3 Energy consumption in shrimp culture system (exclude offices)

2.3.1 Itemized energy consumption (if data is not available for 2.3.1, please complete 2.3.2. Ideally, you could complete both)

a. Oxygen supplement equipment

□ Aeration equipment type (i.e. floating paddlewheel, submersible aerator): ________________

Number of equipment:______; power:____kW or Horse Power (HP); Usage time:______hours/day (week)

□ Oxygen generator

Number of equipment: ________; power: _______kW or HP; Usage time: ______hours/day (week)

□ Other oxygen supplement equipment_____________________

Number of equipment: _______; power: _______kW or HP; Usage time: _______hours/day (week)

b. Ozone generator

Number of ozone generator: _____; power: ______kW or HP; Usage time: _______hours/day (week)

c. Lighting

There are several types of lights with different power and usage time:

Number of light-1: _______; Bulb wattage: _______W; Usage time: _______ hours/day (week)

Number of light-2: _______; Bulb wattage: _______W; Usage time: _______ hours/day (week)

Number of light-3: _______; Bulb wattage: _______W; Usage time: _______ hours/day (week)

d. Pump

Aquaculture system often uses several types of pump. (HP: Horse Power)

Number of pump-1: ____; Pump-1 power: _______kW or HP; Usage time: _______hours/day (week)

Number of pump-2: ____; Pump-2 power: _______kW or HP; Usage time: _______hours/day (week)

Number of pump-3: ____; Pump-3 power: _______kW or HP; Usage time: _______hours/day (week)

Number of pump-4: ____; Pump-4 power: _______kW or HP; Usage time: _______hours/day (week)

e. Air Conditioner

Number of conditioners: ___; Conditioner power: _______kW; Usage time: ______hours/day (week)

f. Heating (source of heating: natural gas): ___________Btu (CCF)/month (year)   (CCF: 1000 $feet^3$)

g. Energy consumption by other equipment

Please list other equipment and energy consumption in shrimp culture system

- Equipment A Name: _____; Number of equipment: _____; Usage time: _____hours/ day (week)
  Power: _______kW(electricity) or Btu/hour or m^3/hour (Natural Gas);
- Equipment B Name: _______; Number of equipment: ____; Usage time: _____hours/ day (week)
  Power: _______kW(electricity) or Btu/hour or m^3/hour (Natural Gas);
- Equipment C Name: _______; Number of equipment: ____; Usage time: _____hours/ day (week)
  Power: _______kW(electricity) or Btu/hour or m^3/hour (Natural Gas);
- Equipment D Name: _______; Number of equipment: ____; Usage time: _____hours/ day (week)
  Power: _______kW(electricity) or Btu/hour or m^3/hour (Natural Gas);

2.3.2 Total utility bill in shrimp culture system (ideally you will complete both 2.3.1 and 2.3.2)

a. Electricity: _______ kWh/month or year

b. Heating: ________Btu/ month or year or Natural Gas: _______m^3/month or year

c. Diesel: _______ gallons or L/month or year

d. list any other type of energy consumption

- Energy 1 (i.e. solar, hydropower, wind): _______
  Consumption Quantity per year or month: _______________/year or month
- Energy 2 (i.e. solar, hydropower, wind): _______
  Consumption Quantity per year or month: _______________/year or month

3. Recirculating Water Treatment System (WTS)

Please write a paragraph and sketch a process flow diagram to describe your water treatment system. In the description and flow diagram, please indicate basic information and significant features/parameters about the water treatment system. The following questions may give you some guidance.

What materials (i.e. chemicals, microorganisms) and method (i.e. biofilter, bio-ball) are used to treat the water; How to maintain the treatment system (i.e. replace oyster shell, clean and refill bio-balls);

How to treat the wastes from system (i.e. used biofilter, sludge);

Number of water treatment tanks: __________; size of each tank: __________m^3($feet^3$)

Land cover of water treatment system (exclude offices): ___________ acres ($feet^2$)

Description of water treatment system:

Please sketch a process flow diagram of the Water Treatment System

3.1 Biofilter Media

Composition of biofilter media used in the water treatment system:

a. Commercial biofilter media

□ Bio-deck or bio-strata: brand_____________________________; Price_________$/ feet^3 (m^3)
The size of biofilter media used in water treatment system_________feet^3 or m^3
How many times is one bio-deck reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year (month)

□ Bio-ball: brand_________________________________; Price_________$/ball
How many bio-balls are used in water treatment system? __________;
Size of one bio-ball: ______fluid ounce (ml)/ball;
How many times is one bio-ball reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year (month)

□ Bio-fill: brand_____________________________________; Price_________$/ feet^3 (m^3)
The size of bio-fill used in water treatment system_________feet^3 or m^3
How many times is one bio-fill reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year (month)

□ Bio-barrels: brand___________________________________; Price_________$/ barrel
How many bio-barrels used in water treatment system? ________;
size of one barrel: ________ fluid ounce (ml);
How many times is one bio-barrel reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year (month)

□ Open-cell foam: brand__________________________________; Price_________$/ feet^3 (m^3)
The size of foam used in water treatment system:_________feet^3 or m^3
How many times is one foam reused (including the first time)?_________

How often do you replace used biofilter media? ___________times/ year (month)

 Matala mat: brand___________________________________; Price_________$/ feet^3 (m^3)
The size of mat used in water treatment system:_________feet^3 or m^3
How many times is one mat reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year

Other commercial media (i.e. bio-glass, biocord, biofilter media bag):
 Brand______________________________; Price_________$/ feet^3 (m^3)
The size of biofilter media used in water treatment system:_________feet^3 or m^3
How many times is one biofilter media reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year
 Brand_______________________________; Price_________$/each
How many biofilter media are used in water treatment system? __________;
size: ______gallon (m^3)/each;
How many times is reused (including the first time)?_________
How often do you replace used biofilter media? ___________times/ year (month)

b. Home-made biofilter media
Clinker: Price_________$/ feet^3 (m^3)
How much media is used in water treatment system? _________feet^3 or m^3;
How many times is media reused (including the first time)?_________
How often do you replace used media? ___________times/ year

Gravel: Price_________$/ feet^3 (m^3)
How much media is used in water treatment system? _________feet^3 or m^3;
How many times is media reused (including the first time)?_________
How often do you replace used media? ___________times/ year

Sand: Price_________$/ feet^3 (m^3)
How much media is used in water treatment system? _________feet^3 or m^3;
How many times is media reused (including the first time)?_________
How often do you replace used media? ___________times/ year

Activated carbon: Price_________$/ feet^3 (m^3)
How much media is used in water treatment system? _________feet^3 or m^3;
How many times is media reused (including the first time)?_________
How often do you replace used media? ___________times/ year

3.2 Other material used to treat water:
Ozone: ___________m^3 (gallon)/ cycle (year); Price: ____________$/ m^3 (gallon)
Oyster shell: ___________lb (kg)/cycle (year); Price: ____________$/lb (kg)
How many times is shell reused (including the first time)?_________
How often do you replace used material? ___________times/ year

Chlorine ___________ lb (kg)/cycle (year); Price: ____________$/lb (kg)
Formalin___________gallon (L)/cycle (year); Price: ____________$/ L(gallon)
Lime ___________ lb (kg)/cycle (year); Price: ____________$/lb (kg)
BKC (Benzakonium chloride):_______ gallon (L)/cycle (year); Price: _______$/ L(gallon)
Other material a: name__________; ____ lb (gallon)/cycle (year); Price: _____$/ lb(gallon)
Other material b: name__________; ____ lb (gallon)/cycle (year); Price: _____$/ lb(gallon)

3.3 Wastes from Water Treatment System

a. Biomass (waste from biofilter media)
Weight: _______lb (kg)/cycle(year); treatment: ☐ Landfill ☐ Incineration ☐ Other: ______
b. Solid sludge
Weight: ________lb(kg)/cycle(year); treatment: ☐ Landfill ☐ Incineration ☐ Other: _______
c. Other waste name: ________________
Weight: ________ lb(kg)/cycle(year); treatment: ☐ Landfill ☐ Incineration ☐ Other: ______

3.4 Energy Consumption in Water Treatment System (exclude offices)

3.4.1 Itemized energy consumption (if data is not available, please complete 3.4.2. Ideally you could complete both)

a. Oxygen supplement equipment (HP: Horse Power)
☐ Aeration equipment (i.e. floating paddlewheel, submersible aerator): ________________
Number of equipment: _______; power: _______kW or HP; Usage time: _______hours/day (week)

☐ Oxygen generator
Number of equipment: _______; power: _______kW or HP; Usage time: _______hours/day (week)
☐ Other oxygen supplement equipment_____________________
Number of equipment: _______; power: _______kW or HP; Usage time: _______hours/day (week)

b. Ozone generator
Number of ozone generator: ____; power: _______kW or HP; Usage time: _______hours/day (week)

c. Lighting
There are several types of lights with different power and usage time.
Number of light-1: _______; Bulb wattage: _______W or HP; Usage time: _____ hours/day (week)
Number of light-2: _______; Bulb wattage: _______W or HP; Usage time: _____ hours/day (week)
Number of light-3: _______; Bulb wattage: _______W or HP; Usage time: _____ hours/day (week)

d. Pump
Water treatment system often uses several types of pump:
Number of pump-1: ____; Pump-1 power: _______kW or HP; Usage time: _______hours/day (week)
Number of pump-2: ____; Pump-2 power: _______kW or HP; Usage time: _______hours/day (week)
Number of pump-3: ____; Pump-3 power: _______kW or HP; Usage time: _______hours/day (week)
Number of pump-4: ____; Pump-4 power: _______kW or HP; Usage time: _______hours/day (week)

e. Air Conditioner
Number of conditioners: ___; Conditioner power: ______kW; Usage time: _______hours/day (week)

f. Heating (source of heating: natural gas): ________________Btu (CCF)/month (year)

g. Energy consumption for other equipment
Please list other equipment and energy consumption in shrimp culture system

□ Equipment A Name:____________; Number of equipment:__; Usage time: _____hours/day (week)
Power: _______kW or HP (electricity) or Btu/hour or CCF/hour (Natural Gas);

□ Equipment B Name:____________; Number of equipment:__; Usage time:_____hours/ day (week)
Power: _______kW or HP (electricity) or Btu/hour or CCF/hour (Natural Gas);

□ Equipment C Name:____________; Number of equipment:__; Usage time:_____hours/ day (week)
Power: _______kW or HP (electricity) or Btu/hour or CCF/hour (Natural Gas);

□ Equipment D Name:____________; Number of equipment:__; Usage time:_____hours/ day (week)
Power: _______kW or HP (electricity) or Btu/hour or CCF/hour (Natural Gas);

3.4.2 Total utility bill in water treatment system

You could get the data for 3.4.2 from monthly or annual bills from your energy supplier. We hope you will complete both 3.4.1 and 3.4.2.

a. Electricity: _______ kWh/month or year

b. Natural Gas (propane): _______m^3 (CCF)/month (year)

c. Diesel: _______gallons (L)/month (year)

d. list any other type of energy

□ Energy 1 (i.e. solar, hydropower, wind): _______
Consumption Quantity per year or month: _______________/year or month

□ Energy 2 (i.e. solar, hydropower, wind): _______
Consumption Quantity per year or month: _______________/year or month

B. Pre-Farming: Hatchery (post-larvae source)

Name of hatchery: ____

Location (City/State/Zip code): ____

Transportation from hatchery to shrimp farming system:

Vehicle Type:

□ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other vehicle:____________

Vehicle Load: _________lb (kg) post-larvae/ vehicle

Would you like us to put your hatchery name in acknowledge of this research?

□ Yes □ No

Would you like to provide more information about the hatchery if future research needed?

□ Yes □ No

C. Post-Farming

The shrimp produced by farm: □ has commercial market □ is sold by shrimp farm directly

If the shrimp product has commercial market, please answer the following questions about shrimp processing/storage and wholesaler/ retailer:

1. Processing & Storage

Shrimp processing plant location (City/State/Zip code): __________________________

Product selling unit: _________lb (kg) shrimp/selling unit

What process is conducted on the shrimp?

□ shelling □ heading □ deveining □ Other process (i.e. tail removal):________________

Waste:

Waste percentage per shrimp: _______% waste per shrimp

Waste handling (i.e. municipal disposal): _____________

Transportation from shrimp farming system to shrimp processing plant:

Vehicle type:

□ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

Product freezing:

If the product is not frozen in processing plant, please provide transportation information from processing plant to freezing plant

Shrimp freezing plant location (City/State/Zip code): __________________________

Vehicle type: □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

2. Wholesaler & Retailer

2.1 Wholesaler and Transportation from Processing/Freezing Plant to Wholesaler

□ Wholesaler 1 location (City/State/Zip code): __________________________

Vehicle type:

□ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Wholesaler 2 location (City/State/Zip code): __________________________

Vehicle type:

□ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Wholesaler 3 location (City/State/Zip code): __________________________

Vehicle type:

□ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Wholesaler 4 location (City/State/Zip code): __________________________

Vehicle type:

□ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

2.2 Retailer (i.e. supermarket) and Transportation from Wholesaler to Retailer

□ Retailer location 1 (City/State/Zip code): __________________________

Vehicle type: □ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Retailer location 2 (City/State/Zip code): __________________________

Vehicle type: □ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Retailer location 3 (City/State/Zip code): _________________________

Vehicle type: □ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______

Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Retailer location 4 (City/State/Zip code): ___________________________
Vehicle type: □ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______
Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

□ Retailer location 5 (City/State/Zip code): ___________________________
Vehicle type: □ Airplane □ Truck w/o Refrigerator □ Truck w/ Refrigerator □ Other_______
Vehicle Load: _________ lb (kg) shrimp /vehicle or _______selling unit/vehicle

D. Total Cost of Indoor Recirculating Shrimp Farm System

Regarding the above questions about the material prices, if individual material's price is not available, please complete the following table. Ideally, we hope you provide both the individual material price and annual category cost, so that we can compare these two set of data.

In the following table, you need to provide category cost in shrimp culture system and water treatment system. You may find such data from annual accounting summary of purchasing material.

Cost Category Unit: thousand dollars	Shrimp Culture System (SCS)	Water Treatment System (WTS)	Whole Recirculating System (SCS+WTS)
Initial Investment			
Material/year	/year	/year	/year
Water/year	/year	/year	/year
Heating/year	/year	/year	/year
Electricity/year	/year	/year	/year
Waste Disposal/year	/year	/year	/year
Transportation/year	/year	/year	/year
Maintenance &Repair/year	/year	/year	/year
Labor/year	/year	/year	/year

Explanation of cost category:

1. Initial investment cost or one time start-up costs includes Land Acquisition, Site Investigation, Design Services, Construction, Equipment and Technology

2. Annual Operation Cost category includes the following items:
   a. material cost (exclude water): cost of all the materials used to culture shrimp and treat water, i.e. post-larva, shrimp feed, water treatment chemicals, biofilter media,
   b. water cost: the freshwater and saltwater used in shrimp culture system and water treatment system
   c. energy cost: heating and electricity cost in Shrimp Culture System and Water Treatment System
   d. waste disposal cost: the cost to handle the waste from shrimp culture system (i.e. biomass) and water treatment system (i.e. biomass and sludge)
   e. transportation cost: fuel cost to transport materials and water from material suppliers to farm; it could also include the fuel cost to transport shrimp product from farm to processing plant. Please indicate what transportation is included in the transportation cost you listed in the above table:

3. Maintenance and Repair Cost includes routinely maintenance and repair of building systems or components, i.e. Equipment & Furnishings, Site Improvements, Site Utilities, Foundation/Substructure, Superstructure, Walls, Windows, Doors, Floors, Roofs, Ceiling, Interior Partitions, Conveyance Systems, Plumbing Piping, Plumbing Fixtures, Fire Protection Systems, Heating, Ventilating and Air Conditioning, Electrical Service/Distribution, Lighting

4. Labor Cost: employee cost

E. Confidential Issues

Among the above information/data, if there is any information/data you do not want to show in the future published document, please indicate here.

Thanks for your help!

Appendix 2 Detailed calculation processes for the design of a commercial-scale recirculating aquaculture system

1	*Hawaii OI: Assumptions and Design for 1500 m2 or 5 ponds*					
2	**Culture and Water Treatment System**					
3	**1. Growout/Culture Raceway Design**	**Parameter**	**Value**	**Unit**	**Calculation Formula**	**Data source**
4	pH		6.5-7	pH	6.5-7	
5	Temperature		23-34	°C	23-34	
6	Pond Dimention		300.00	m2	300.00	WMC
7		L	20.00	m	20.00	WMC
8		W	15.00	m	15.00	WMC
9		H	1.60	m	1.60	WMC
10	Design Objective culture area		1500.00	m2	1500.00	WMC
11	Water Depth		1.60	m	1.60	WMC
12	Water Volume		2400.00	m3	=D10*D11	
13	Max culture density		10.00	kg shrimp/m2	10.00	Max value of WMC and OI
14	Max shrimp biomass		15000.00	kg shrimp	=D13*D10	
15	Feeding Rate % of Shrimp Weight		0.03		0.03	Assume
16	Feeding Rate	FR	450.00	kg feed/day	=D14*D15	
17	Feed Content					
18	Protein content of Feed	PC	0.30		0.30	Rangen shrimp feed
19	N content in protein		0.16		0.16	
20	Percentage of N assimilated		0.80		0.80	TL book, Equ 2.10, P16, (assume non-asssimilated N
21	Percentage of assimilated N is excreted		0.80		0.80	in fecal matter is removed from tank rapidly)
22						
23	**2. Flow Rate Design**					
24						
25	**2.1 Oxygen Mass Balance**					
26	submerged external treatment? (0=No, 1=Yes)		0.00		0.00	settler
27	O2 used by nitrification in external treatment syste		0.00	kg O2/day	=D26*D48*D49*4.57	
28	O2 used by nitrification in raceway		54.40	kg O2/day	=D47*4.57	
29	O2 used/produced by phytoplankton photosynthes		0.00	kg O2/day	0.00	Assume the net O2 by phytoplankton is zero
30	Oxygen used per kg feed		0.30	kg O2/kg feed	0.30	Assume
31	Oxygen used by shrimp related w/ feed addition		135.00	kg O2/day	=D16*D30	
32	Total O2 consumption per day	Ro	189.40	kg O2/day	=SUM(D27:D29,D31)	
33	DO concentration in Influent from oxyg	Coi	39.00	mg O2/L	39.00	Assume based on the O2 conc. of water effluent from oxygenation system
34	Desired DO concentration in tank	Co	5.00	mg O2/L	5.00	Assume
35	Production Rate of DO by aeration	Po	0.00	kg O2/day	0.00	Assume based on the O2 production of paddle wheels
36	Flow Rate required for DO maintenanc	Q	5570626	L/day	=(D32-D35)/(D33-D34	TL book, Equ 2.5
37			3.87	m3/min	=D36/1000/24/60	
38						

39	**2.2 Ammonia-Nitrogen Control**					
43	Desired TAN concentration in culture ta	Ctan	2.00	mg N/L	2.00	Losordo & Hobbs, 1999. make sure designed paramete
44	Removal rate of TAN by phytoplankton in raceway		1.76	mg N/L/day	1.76	Brune 2003 (R=1.760-2.113 mg/L/day and 0.5mg N/L/d)
45	Removal rate of TAN by nitrification in raceway		3.20	mg N/L/day	3.20	Rakocy et al. 2004 (0.125kg feed/day/m3, R=3.2mg N/L/day)
46	Removal rate of TAN by biofloc in raceway		4.96	mg N/L/day	=D45+D44	
47		Ptan	11.90	kg N/day	=D46*D12*1000/1000000	
48	Production rate of TAN	Ptan	13.82	kg N/day	=D16*D18*D19*D20	TL book, Equ 2.10, P16. The equation present a conservatively high estimate of the TAN prodution
49	nitrogen removal effi by external treatment		0.10		0.10	Assume
50	TAN in water influent after external treatment		1.80	mg N/L	=D43*(1-D49)	
51	Water flow rate requirement		9600000	L/day	=(D48-D47)/(D43-D50)*1000000	
52	TAN available after biofloc removal		1.92	kg N/day	=D48-D47	
53						
54	**2.3 Nitrate Control**					
55	Max nitrate allowed in the system	C(NO3)	150	mg N/L	150	Losordo & Hobbs, 1999
56	Passive denitrification		0		0	Assume no denitrification occurs
57	Flow Rate required for nitrate control	Q	12800	L/day	=D52*(1-D56)/D55*1000000	
58						
59	**2.4 Solids Mass Balance**					
60	percentage of feed becoming solid waste		0.25		0.25	Losordo & Hobbs, 1999
61	waste solids produced		450.00	kg SS/day	=D16	
62	Desired SS conc. In raceway		700.00	mg/L	700.00	Rakocy 2004 (20-25/m3, TSS 476-898 mg/L) and Burford 2003 (TSS 38-84mg/L, 120 shrimp/m2)
63	SS removal effi by settler		0.70		0.70	Assume
64	SS removal effi by foam fractionater		0.60		0.60	
65	Total SS removal effi		0.88		=1-(1-D63)*(1-D64)	
66	Flow rate required		730519	L/day	=D61/D62/D65*1000000	
67						
68	**2.5 design flow rate**					
69	5 ponds		9600000	L/day	=MAX(D36,D51,D57,D66)	
70			6666.67	L/min	=D69/24/60	
71			1761.34	gpm	=D70/3.785	
72	1 pond		1920000	L/day	=D69/5	
73			1333	L/min	=D70/5	
74			352	gpm	=D71/5	
75						
76	**3. Settler**					
77	# of ponds served		5		5	
78	Settling velocity of the smallest partic	Vo	40.00	m/d	40.00	TL book, P78 (range 40-80m/d)
79	Retention time	R	1.00	h	1.00	Assume
80	Settler Area	A	240.00	m2	=D72*D77/D78/1000	
81	Settler volume required	V	400000	L	=D77*D72*D79/24	
82			400	m3	=D81/1000	
83	Settler Height required	H	1.67		=D82/D80	
84	Design dimension					
85		L	15.00	m	15.00	
86		W	12.00	m	12.00	
87		H	2.5	m	2.5	
88	volume	V	450.00	m3	=D85*D86*D87	
89						
90	**Equipments**					
91						
92	**2. Oxygenation (O2 generator + contactor)**					
93	Air Products O2 generator outlet gas	density	1300.00	g/m3	1300.00	Assume based on product MSDS
94		flow rate	150.00	L gas/min	150.00	
95			195.00	g O2/min	=D93*D94/1000	
96	# of generators per pond		1.30		=13/10	OI (1 greenhouse has 13 generators)
97	# of ponds served		5.00		5.00	
98	Cone bubble contactor Absorption Effi		0.90		0.90	Assume
99	DO difference in water flow		1140.75	g O2/min	=D95*D96*D97*D98	
100			171.11	mg O2/L	=D99/D73/D97*1000	
101	DO influent to generator		5.00	mg O2/L	5.00	Assume
102	DO effluent from generator		176.11	mg O2/L	=D100+D101	
103	Oxygenation meet O2 maintenance requirement?		Yes		=IF(D102>D33,"Yes","No")	
104	Air Products O2 generator dimension	Equipment enclosure with oxygen generation tank (2.11 m L x				Air Products description
105		Oxygen buffer tank (1 m Dia. x 2.36 m L)				
106	Cone bubble contactor dimension	Diameter 0.7 m, height 2m				Assume
107	**6. Foam Fractionator**					
108	# of foam fractionator in one greenhouse		4.00		4.00	WMC
109						
110	**Reference:**					
111	Brune et al. 2003, Intensification of pond aquaculture and high rate					
112	Burford et al. 2003, Nutrient and microbial dynamics in high-intensity, zero-exchange shrimp ponds in Belize					
113	Losordo & Hobbs 1999, Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems					
114	OI: Oceanic Institute					
115	Rakocy et al. 2004, Intensive tank culture of tilapia with a suspended, bacterial-based, treatment process					
116	TL book: Aquaculture water reuse systems: engineering design and management, Michael B. Timmons and Thomas M. Losordo, 1994 Elsevier Science					
117	WMC: Waddell Mariculture Center					

Appendix 3 Detailed calculation processes of broodstock consumption

I assumed one female broodstock produced 100,000 eggs each time spawning occurred, which was 4 times during the organism?s life cycle. I also assumed 85% of broodstock would spawn and 60% of the eggs would survive. So one female broodstock produced 100000eggs/broodstock/time*4times*85%*60% = 204,000eggs or 204,000 PL, which meant 0.0049 female broodstock was needed for 1000 PL production. Since the ratio of female broodstock to male broodstock was assumed to be 2:1, total number of broodstock needed for 1000 PL production was 0.0049/2*3 = 0.0074. The following spreadsheet presents the parameters used in this calculation.

Amount	**Unit**
100,000	eggs/time/female broodstock
4	times
400,000	eggs/female broodstock
85%	(female broodstock spawning rate)
60%	(egg survival rate)
204,000	eggs/female broodstock
204,000	PL/female broodstock
4.9E-06	female broodstock/PL
0.0049	female broodstock/1000PL
2	female:male (broodstock)
0.0074	broodstock/1000PL

Appendix 4 Energy intensities of constructional materials

Energy Intensity	**Amount (MJ LHV/kg)**
LDPE	80
sawn timber	13,856
plywood	32,967
concrete	2
HDPE	74
PVC	67

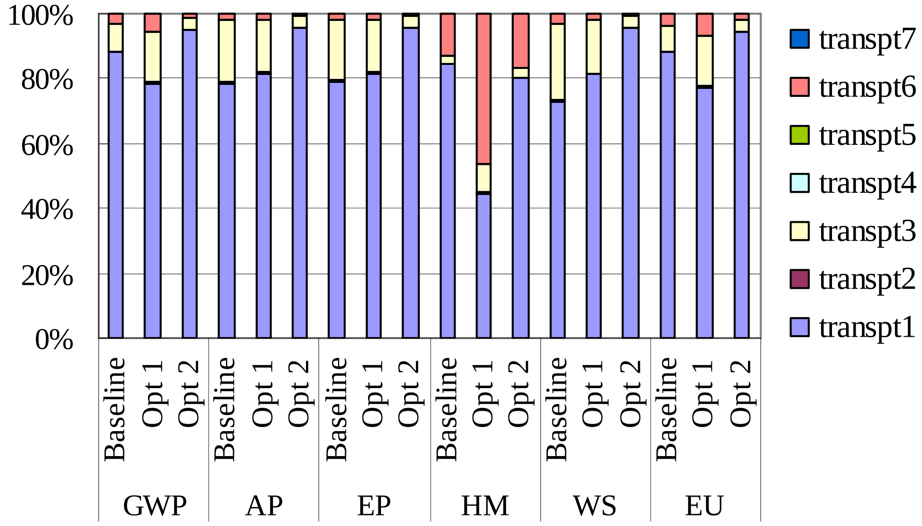
Appendix 5 Impact intensities from SimaPro database (Eco-indicator 95)

Impact category	Unit	Fishmeal (kg)	Electricity (MJ)	Salt (kg)	Truck (tkm)
Greenhouse	kg CO2	0.711937	0.200458	0.179206	0.208967
Ozone layer	kg CFC11	1.38E-06	4.21E-09	5.76E-08	1.69E-10
Acidification	kg SO2	0.004304	0.002027	0.00216	0.002358
Eutrophication	kg PO4	-0.00671	9.31E-05	0.000198	0.000343
Heavy metals	kg Pb	2.74E-06	5.5E-07	4.51E-07	9.86E-08
Carcinogens	kg B(a)P	3.52E-08	5.29E-10	1.1E-09	9.39E-11
Pesticides	kg act.subst	0	0	0	0
Summer smog	kg C2H4	0.000702	6.06E-05	0.001709	0.00038
Winter smog	kg SPM	0.002204	0.001555	0.0011	0.001079
Energy resources	MJ LHV	15.91207	3.431506	2.81617	2.883681
Solid waste	kg	0	0.033985	0.03506	0.001095

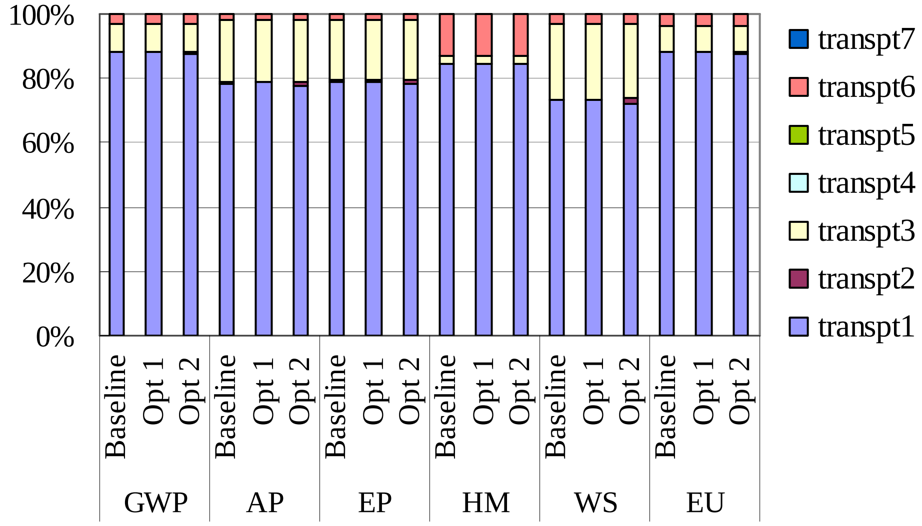
Appendix 6 Normalization values for Eco-indicator 95 (Goedkoop, 1995)

Impact Category	**Unit**	**Per head of the population**
Greenhouse	kg CO_2	1.31E+04
Ozone layer	kg CFC-11	9.26E-01
Acidification	kg SO_2	1.13E+02
Eutrophication	kg PO_4	3.82E+01
Heavy metals	kg Pb	5.43E-02
Carcinogens	kg B(a)P	1.09E-02
Pesticides	kg act.subst	9.66E-01
Summer smog	kg C_2H_4	1.79E+01
Winter smog	kg SPM	9.46E+01
Energy resources	MJ LHV	1.59E+05
Solid waste	kg	N/A

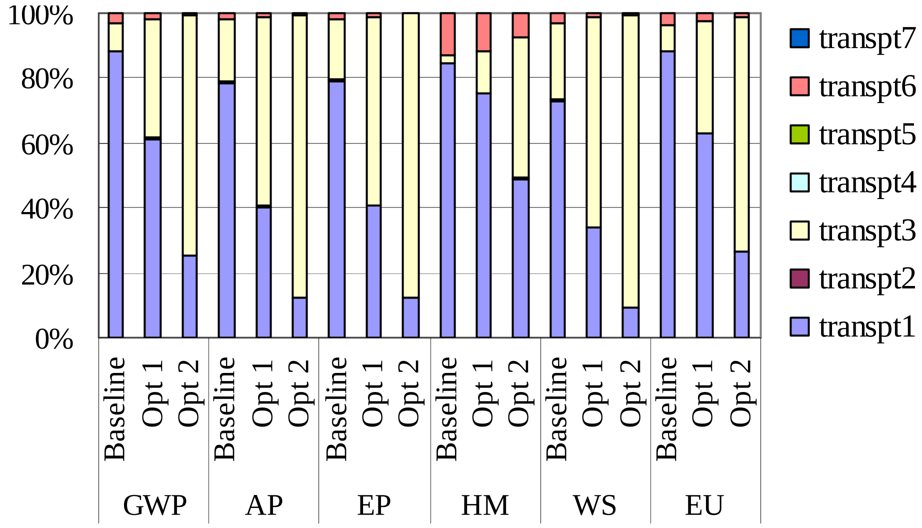
Appendix 7 Distribution of transportation stage for (a) Transportation 1, (b) Transportation 2, (c) Transportation 3, (d) Transportation 4 and (e) Transportation 6 scenario analysis



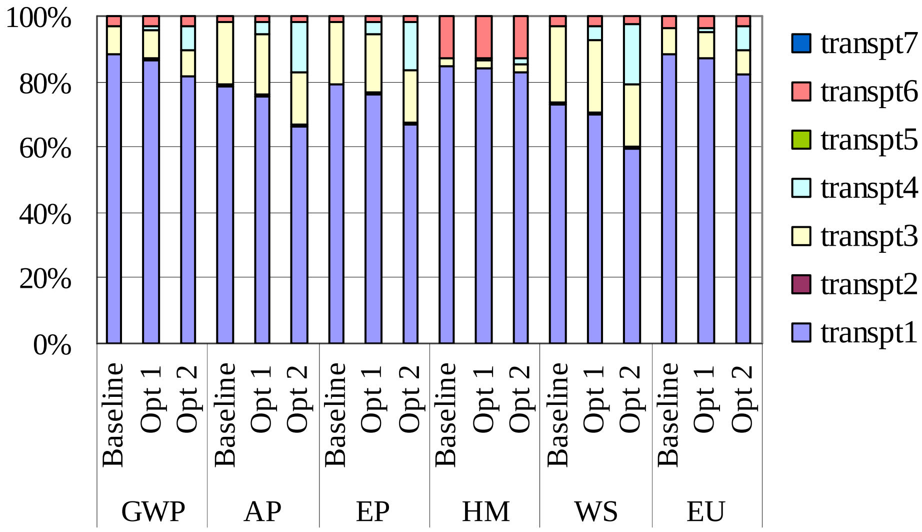
a) from feed raw material suppliers to feed mill (Transportation 1)



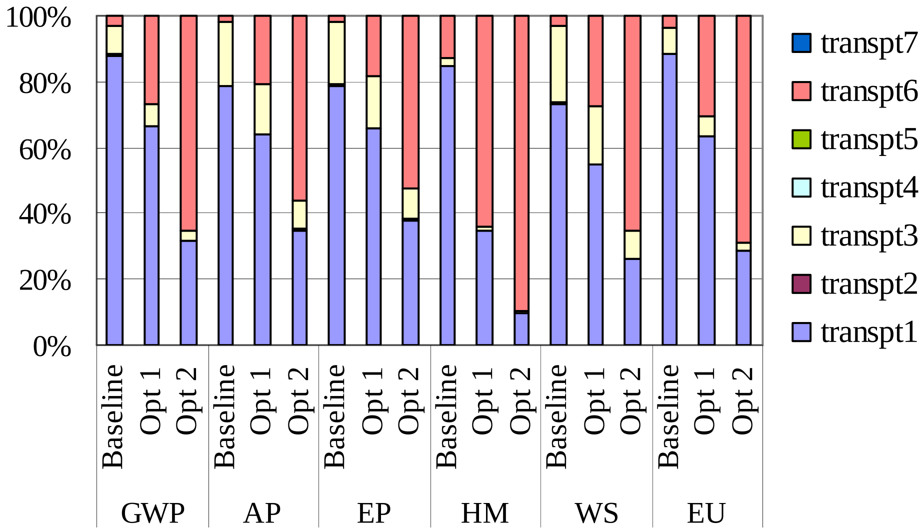
b) from feed mill to hatchery (Transportation 2)



c) from feed mill to farm (Transportation 3)



d) from hatchery to farm (Transportation 4)



e) from farm to consumer (Transportation 6)