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Life Cycle Assessment of Chinese Shrimp Farming Systems Targeted for Export and Domestic Sales

Ling Cao,*[†] James S. Diana,[†] Gregory A. Keoleian,[†] and Qiuming Lai[‡]

[†]School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109, United States

[‡]Ocean College, Hainan University, Haikou, China

S Supporting Information

ABSTRACT: We conducted surveys of six hatcheries and 18 farms for data inputs to complete a cradle-to-farm-gate life cycle assessment (LCA) to evaluate the environmental performance for intensive (for export markets in Chicago) and semi-intensive (for domestic markets in Shanghai) shrimp farming systems in Hainan Province, China. The relative contribution to overall environmental performance of processing and distribution to final markets were also evaluated from a cradle-to-destination-port perspective. Environmental impact categories included global warming, acidification, eutrophication, cumulative energy use, and biotic resource use. Our results indicated that intensive farming had significantly higher environmental impacts per unit production than semi-intensive farming in all impact categories. The grow-out stage contributed between 96.4% and 99.6% of the cradle-to-farm-gate impacts. These impacts were mainly caused by feed production, electricity use, and farm-level effluents. By averaging over intensive (15%) and semi-intensive (85%) farming systems, 1 metric ton (t) live-weight of shrimp production in China required 38.3 ± 4.3 GJ of energy, as well as 40.4 ± 1.7 t of net primary productivity, and generated 23.1 ± 2.6 kg of SO_2 equiv, 36.9 ± 4.3 kg of PO_4 equiv, and 3.1 ± 0.4 t of CO_2 equiv. Processing made a higher contribution to cradle-to-destination-port impacts than distribution of processed shrimp from farm gate to final markets in both supply chains. In 2008, the estimated total electricity consumption, energy consumption, and greenhouse gas emissions from Chinese white-leg shrimp production would be 1.1 billion kW·h, 49 million GJ, and 4 million metric tons, respectively. Improvements suggested for Chinese shrimp aquaculture include changes in feed composition, farm management, electricity-generating sources, and effluent treatment before discharge. Our results can be used to optimize market-oriented shrimp supply chains and promote more sustainable shrimp production and consumption.

INTRODUCTION

Aquaculture is of great importance worldwide, serving as an alternative source to traditional food production systems and helping supply the expansion of human population. Global production of shrimp farming has increased from less than 9000 metric tons in 1970 to more than 3.2 million metric tons in 2008.[1] Most production occurs in Asia, mainly China and Thailand.[2] International trade of aquaculture products is a means to promote economic growth and alleviate poverty in most developing countries.[3] Shrimp is the most traded seafood product.[4] In 2008, shrimp aquaculture ranked second in world aquaculture production in value and fourth in quantity.[1] The boom of Chinese shrimp farming has been triggered by growing demand, mainly from international markets in the United States, the European Union, and Japan. Increase of export-oriented shrimp production is achieved with intensification of farming systems by large commercial companies, which have greater farm size, material inputs, energy demands, and effluent discharge.[5] However, the majority of shrimp production in China is still based on traditional techniques from small farms, directed to feed the local population and not for export. The expansion of shrimp farming has generated global concerns over its negative environmental impacts on aquatic ecosystems and human livelihoods in coastal areas.[3] These impacts include biodiversity depletion, eutrophication, land modification, and food insecurity. There is debate over whether shrimp farming can be sustainable and how to promote more sustainable export-oriented farming systems. Growing awareness of environmental problems during recent years has led to increasing demand for environmental performance information from different shrimp farming systems.

Evaluating macro-level environmental impacts of shrimp farming systems requires a full evaluation of activities that comprise the whole supply chain. Life cycle assessment (LCA)

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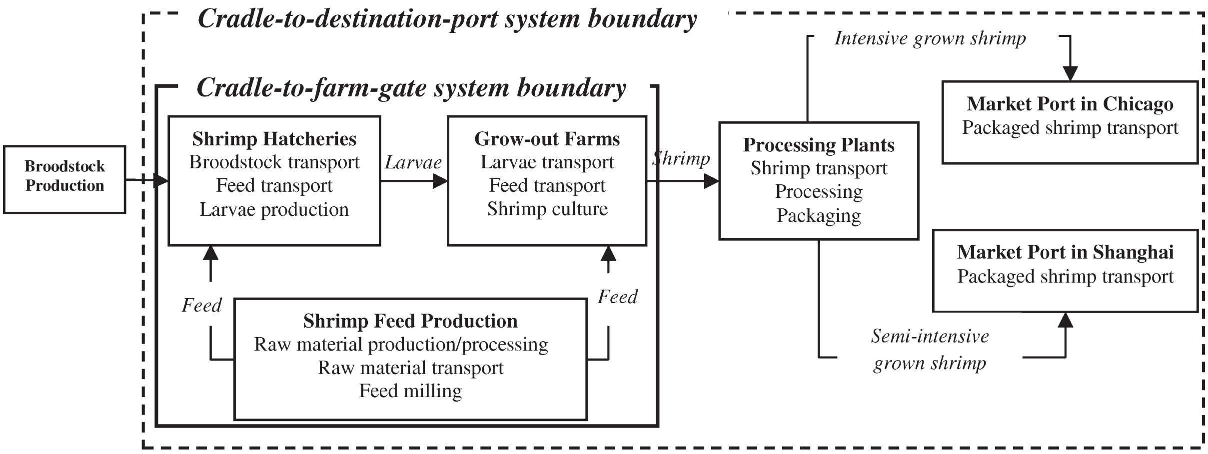

Figure 1. Life cycle flowchart and system boundaries for LCA of shrimp produced in China and distributed to domestic (Shanghai) and export (Chicago) markets.

can be used to make such an evaluation, quantifying potential environmental burdens throughout the life cycle of shrimp production. It can be used to calculate the energy and material usage in an overall process.[3] LCA can also provide a framework for evaluating environmental performance and identifying the major processes in energy use, as well as global warming, acidification, and eutrophication impacts. It has been widely applied to evaluate seafood products.[6−13] Nevertheless, LCA is a less developed and standardized tool for assessing local ecological and socio-economic impacts. Those impacts could be described quantitatively on a functional unit basis or qualitatively.[14] Impact assessment is generally highly uncertain and less standardized than inventory analysis.

This study employs LCA to quantify and compare cradle-to-destination-port environmental impacts associated with white-leg shrimp (*Litopenaeus vannamei*) production in China directed toward domestic or export markets in the United States. Domestic markets are usually linked to traditional semi-intensive farming, which mainly use shrimp larvae produced by local broodstock. Export-oriented production is intensive farming which grows shrimp larvae produced by imported broodstock from Hawaii. We are particularly interested in examining biotic resource use, cumulative energy use, global warming, eutrophication, and acidifying emissions associated with shrimp production for both markets, which are typically employed in seafood production.[14] The objectives of this study are to (1) identify key stages and hotspots with highest contribution to overall impacts and assess the most significant environmental impacts, (2) compare how these two market-oriented production systems (intensive and semi-intensive) differ in their environmental performance, (3) evaluate the contribution to overall environmental performance of transporting frozen shrimp products to export markets, and (4) use the LCA results as basis to formulate strategies to minimize environmental impacts and promote more sustainable shrimp production.

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

MATERIALS AND METHODS

System Boundary. Global and regional environmental impacts associated with intensive (for export sale) and semi-intensive (for domestic sale) shrimp supply chains were evaluated by LCA following ISO guidelines.[15] The main system boundary of our study was from cradle to farm-gate, including feed production, production of larvae at hatcheries, and production of marketable-size shrimp at the farm level (Figure 1). The transportation of materials at each step was taken into account. Processing and distribution impacts in transporting the processed shrimp from farm gate to final market port were also evaluated to study their significance in a cradle-to-destination-port system (including cradle-to-farm-gate system, processing, and distribution). The subsequent wholesale, retail, consumption, and disposal of waste were not included. The functional unit was 1 metric ton (t) live weight of shrimp for cradle-to-farm-gate and 1 metric ton (t) of frozen headless shell-on shrimp product for cradle-to-destination port.

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

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

Harvested shrimp are transported directly to processing plants for further processing and packaging. Depending on market requirements, shrimp are processed into different forms such as headless shell-on shrimp, peeled tail-on shrimp, and peeled deveined shrimp. After processing, intensively grown shrimp are exported to international markets in the United States, Japan, and Europe. Shrimp from semi-intensive farms are sold in domestic markets in China. Additional information on system differences is provided in Table S1, Supporting Information.

Life Cycle Inventory. The life cycle inventory (LCI) involved onsite data collection for all the relevant inputs and outputs associated with the two studied supply chains. A total of six hatcheries and 18 farms, which represented different hatchery and farming types, were visited to ensure data quality. The operating data for the 18 farms were average values based on the three most recent years of production. Primary operating data were obtained directly from shrimp feed companies, hatcheries, shrimp farms, and processing plants in Hainan Province, China, in 2008. Shrimp feed composition modeled in the analysis was obtained through records from local feed companies. In each case, head managers were interviewed with detailed questionnaires. Facility records and appropriate estimations by head managers were used to reduce possible errors. Emissions of macronutrients to water associated with shrimp farming were estimated through nutrient balance modeling. The calculations of nitrogen and phosphorus emissions were based on the difference between the amount of nutrients provided to shrimp via feed and fertilizers and the amount assimilated as weight gain.[9] Secondary data such as electricity production, extraction and processing of raw materials, and transportation were obtained from published sources or extensive databases within Simapro 7.1 software and modified appropriately to conform to regional conditions whenever possible (Table S2, Supporting Information).

Life Cycle Impact Assessment. Life cycle impact assessment (LCIA) characterizes environmental impacts based on LCI results. The following environmental impact categories were considered: biotic resource use (BRU, net primary productivity as measured in carbon),[10,16] cumulative energy use (CEU), global warming (GW), acidification (Acd), and eutrophication (Eut). With the exception of biotic resource use, the calculation was processed for data fed into Simapro 7.1 software.[17] Acidification, eutrophication, and global warming impacts were calculated by the problem-oriented (midpoint) CML2 baseline 2000 method (version 2.04).[17] The cumulative energy demand method (version 1.05) was adopted to calculate cumulative energy use.[17] Calculation of BRU followed the method described by Pelletier and Tyedmers.[10] Two shrimp supply chains directed to export markets in Chicago (intensive farming) and domestic markets in Shanghai (semi-intensive farming) were modeled respectively and compared. All impacts were calculated per live-weight metric ton of shrimp for the cradle-to-farm-gate system and per metric ton of frozen headless shell-on shrimp for cradle-to-destination-port system.

Comparison of Different Characterization Methods. Base-case results from CML2 Baseline 2000 method were verified by adopting two different LCIA methodologies available in Simapro software to test the consistency and reliability of results. One end-point method (Eco-indicator 95) and one midpoint and end-point combination method (IMPACT 2002+) were adopted to compare with the current midpoint method (CML2 baseline 2000). Three common impact categories (Acd, Eut, and GW) that were considered important for aquaculture[14] were selected as comparison criteria.

Uncertainty and Sensitivity Analysis. An uncertainty analysis was conducted for environmental impact results based on the set of inventory data collected from 18 different farms (nine farms for each type) to calculate confidence intervals of environmental impacts.

Table 1. Farm-Level Inputs and Outputs (Mean ± SD) for the Production of 1 Metric Ton Live-Weight of Shrimp in China in 2008

materials	intensive farming	semi-intensive farming
	Inputs: Infrastructure[a]	
HDPE[b] linear (kg)	28.4 ± 3.5	
concrete (kg)	1.95 ± 0.4	1.42 ± 0.4
diesel (L)	7.08 ± 1.04	23.9 ± 2.8
PVC[c] pipe (kg)	1.5 ± 0.5	2.3 ± 0.48
	Inputs: Operational	
larvae (no.)	215 000 ± 9100	191 000 ± 8600
sea water (L)	12 100 ± 470	13 000 ± 580
chlorine (kg)	44.7 ± 3. 8	103 ± 7.3
$CaCO_3$ (kg)	419 ± 57	909 ± 76
CaO (kg)	195 ± 22	318 ± 36
triple superphosphate (kg)		28.3 ± 3.8
urea (kg)		21.2 ± 2.5
poultry manure (kg)		283 ± 41
feed (kg)	1600 ± 190	970 ± 170
electricity (kW·h)	2550 ± 220	548 ± 88
	Outputs: Operational	
total nitrogen (TN, kg)	66 ± 12	38 ± 3.7
total phosphorus (TP, kg)	9 ± 1.6	3.5 ± 0.8

[a] Including pond and water management infrastructure. [b] High-density polyethylene. [c] Polyvinyl chloride.

Mean and standard deviation (SD) of inputs and outputs at the farm level were used to construct 95% confidence intervals. As a comparison, Monte Carlo simulation in Simapro was performed with set stop factors of 0.005 to generate 95% confidence intervals[17] to test uncertainty for all impact categories except BRU. Sensitivity analyses were performed to evaluate possible strategies for environmental performance improvement through scenario modeling.

RESULTS

Life Cycle Inventory. Detailed information of inputs and outputs for feed production, larvae production at hatcheries, processing, and transportation at each step are reported in Tables S3−S11, Supporting Information.

Inputs and outputs to larvae production at two different hatcheries (one was an industrial-scale system using imported broodstock from Hawaii and the other was a small-scale system using domesticated broodstock) varied markedly (Table S4, Supporting Information). With relatively lower larvae production, the small-scale system required higher infrastructure and operational inputs and generated more operational outputs per unit of larvae produced. Only transport- and electricity-related inputs were higher in the industrial-scale system. This was because broodstock was imported from Hawaii by air and this advanced system used more energy for water pumping and aeration to keep shrimp and larvae alive at high density. One metric ton of shrimp larvae produced by small-scale hatcheries in China consumed 12 t of feed and 96.5 GJ of electricity, while 8.8 t of feed and 111 GJ of electricity were needed to produce 1 t of larvae in industrial-scale hatcheries.

Table 2. Life Cycle Impacts (Cradle to Farm-Gate) Associated with 1 Metric Ton of Live-Weight Shrimp Produced from the Two Farming Systems[a]

	Acd (kg of SO_2 equiv)	Eut (kg of PO_4equiv)	GW (kg of CO_2 equiv)	CEU (GJ)	BRU (kg of C)
		Intensive Farming			
larvae production	1.15	0.23	188	2.72	0
grow-out infrastructure	0.25	0.02	64.5	2.66	0
feed production	15.8	6.3	2110	28.3	60 700
electricity use	25.2	1.04	2,450	23.2	0
chlorine	0.24	0.02	48.4	0.94	0
limestone	0.03	0.004	5.41	0.12	0
burnt lime	0.55	0.03	270	1.32	0
grow-out effluents	0	55.3	0	0	0
larvae transport	0.21	0.03	56.4	1.02	0
feed transport	0.42	0.07	59.5	0.87	0
other transport	0.17	0.03	24.5	0.36	0
total (mean ± SD)	43.9 ± 4.2	63 ± 11	5280 ± 510	61.5 ± 6.1	60 700 ± 3900
		Semi-intensive Farming			
larvae production	0.5	0.1	70.8	1.07	0
grow-out infrastructure	0.18	0.02	20.5	1.45	0
feed production	9.55	3.82	1,280	17.1	36 800
electricity use	5.41	0.22	526	4.98	0
fertilizer	1.46	1.27	160	3.01	0
chlorine	0.55	0.04	112	2.16	0
limestone	0.06	0.01	11.8	0.27	0
burnt lime	0.9	0.05	441	2.16	0
grow-out effluents	0	26.7	0	0	0
larvae transport	0.11	0.02	29.8	0.54	0
feed transport	0.26	0.05	36.1	0.53	0
fertilizer and other transport	0.44	0.08	61.9	0.91	0
total (mean ± SD)	19.4 ± 2.9	32.3 ± 4.7	2750 ± 400	34.2 ± 4.9	36 800 ± 1900

[a] Acd, acidification; Eut, eutrophication; GW, global warming; CEU, cumulative energy use; BRU, biotic resource use (net primary productivity as measured in carbon).

On-farm material and energy inputs and nutrient effluents showed substantial differences per metric ton of shrimp produced by each farming type (Table 1). Overall, intensive farming had consistently higher on-farm energy and feed use. Higher stocking density and water exchange rates also required more electricity use for aeration and pumping in intensive farming. Relative to semi-intensive systems, on-farm energy use per metric ton of shrimp was 470% higher for intensive systems. The amount of feed required to produce 1 t of shrimp varied from 1600 kg in intensive farming to 907 kg in semi-intensive farming systems. As a result of higher feed usage, farm-level nutrient emissions were also considerably higher in intensive systems. However, with higher stocking density and unit production, intensive farming had lower infrastructure-related inputs, except HDPE linears, which were used only in intensive ponds.

Electricity, water, plastic and cardboard packaging, and ice were the main material and energy inputs to processing operations. Shrimp out of processing plants was frozen, headless, shell-on and packaged (Table S5, Supporting Information). These frozen packaged shrimp products were transported 2500 and 18 500 km by ocean freighter to destination ports in Shanghai and Chicago, respectively.

Life Cycle Impact Assessment. Using life cycle assessment models, contribution analysis focusing on cradle-to-farm-gate shrimp production was conducted to identify the key contributors for each impact category for both farming systems (Table 2). Intensive farming created markedly higher environmental impacts than semi-intensive farming in all five categories: acidification (56% higher), eutrophication (49%), GW (48%), CEU (44%), and BRU (39%). Feed (36−100%) and electricity production (28−57%) dominated in all impact categories except eutrophication for both systems in the grow-out stage. Grow-out effluents contributed 83−88% to eutrophication. By averaging over two farming systems (with the assumption that 85% of farms are semi-intensive and 15% are intensive), 1 t live-weight of shrimp production in China required 38.3 ± 4.3 GJ of energy, as well as 40.4 ± 1.7 t of net primary productivity, and generated 23.1 ± 2.6 kg of SO_2 equiv, 36.9 ± 4.3 kg of PO_4 equiv, and 3.1 ± 0.4 t of CO_2 equiv.

Environmental impacts of the shrimp supply chains from cradle to destination ports were also evaluated. The results of semi-intensive were normalized to the intensive chain in each category (Figure 2a). Semi-intensive systems were 40−50% lower than intensive systems in all impact categories. Confidence intervals (95%) are presented as error bars (Figure 2a), which were calculated as mean ± 1.96SD of inventory data at the farm level. Eutrophication showed the greatest variability, while biotic resource use showed the least. Confidence intervals (95%) were

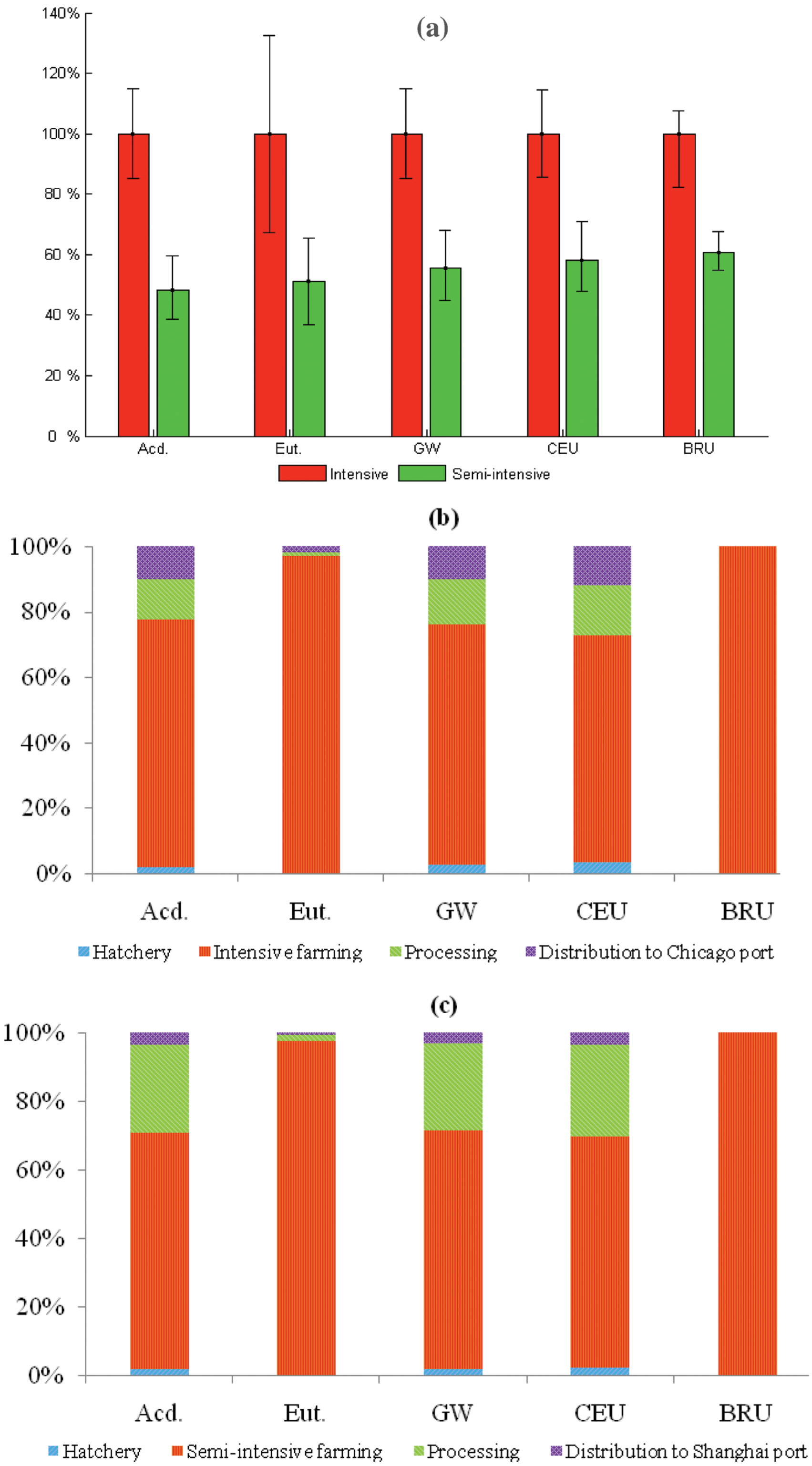

Figure 2. (a) Normalized impacts of semi-intensive relative to intensive supply chain. Error bars represent 95% confidence intervals. (b) Life cycle contribution analyses of intensive farming systems from cradle to Chicago port. (c) Life cycle contribution analyses of semi-intensive farming systems from cradle to Shanghai port.

also determined by Monte Carlo simulation in Simapro for each category except biotic resource use to evaluate uncertainty (Figure S1, Supporting Information). Eutrophication impact had the lowest uncertainty and cumulative energy use had the largest.

Another contribution analysis was performed to identify subsystems with the highest environmental loads in the two shrimp supply chains (Figure 2b,c). Similar patterns occurred in both supply chains. The grow-out stage showed significantly higher contributions to all impact categories compared to hatchery, processing, and transport, and thus it is the key life cycle stage. For cradle-to-destination-port life cycle impacts of shrimp production, grow-out accounted for 69.4−96.8% in intensive and 67.4−99.3% in semi-intensive systems for each impact category. Processing contributions ranged from 0.9% to 15.6% in intensive systems and from 0.6% to 26.8% in semi-intensive systems. Although frozen packaged shrimp was transported a long way to destined ports, transportation contributed only 2−11.8% in intensive systems and 0.6−3.7% in semi-intensive systems in each impact category. Contributions from larvae production at hatcheries were negligible in both supply chains for all impact categories.

Given the importance of shrimp feed, comparative life cycle impacts of shrimp feed production were evaluated (Figure S2, Supporting Information). The major contributors were fishmeal, wheat flour, and feed milling. Fishmeal was the largest contributor to all impact categories other than eutrophication, which was dominated by wheat flour. Fishmeal accounted for 44% of acidification, 47% of global warming, 47% of cumulative energy use, and 91% of biotic resource use. Wheat flour contributed 47% to eutrophication.

Comparison of Characterization Methods. Despite differences in characterization methods and parameters between CML2, IMPACT 2002+, and Eco-indicator 95, all three methods gave similar results for acidification and global warming. IMPACT 2002+ predicted much lower eutrophication for both systems compared to the other two methods (Table S12, Supporting Information).

Sensitivity Analysis Results. We undertook a sensitivity analysis to estimate how global warming would change if the Chinese electricity mix was shifted from coal-dominated to less CO_2-intensive energy. Three alternatives were compared to the baseline: (1) baseline, coal-dominated—coal (65.7%), hydropower (25%), natural gas (7.3%), nuclear (2%); (2) natural gas-dominated—replace coal with natural gas; (3) nuclear dominated—switch coal to nuclear power; (4) hydro-dominated—switch coal to hydro power. Results showed a 25−50% drop in GW when coal was replaced by hydro or nuclear but only a 12−25% drop when coal was replaced by natural gas (Figure S3, Supporting Information). Similar trends occurred for both farming systems.

The effect of feed conversion ratio on environmental performance was modeled for intensive farming systems. Although the average feed conversion ratio (FCR) for the intensive system is 1.6 (1 t of shrimp production consumes 1.6 t of feed), surveyed intensive farms had FCRs ranging from 1.4 to 2. We modeled two cradle-to-farm-gate scenarios with FCR at 1 and 1.3 to compare to the baseline FCR at 1.6 (Figure S4, Supporting Information). Lowering FCR would reduce global warming by 8−16% and biotic resource use by 19−37%.

We also simulated the effect of replacing fish-derived ingredients with crop-derived ingredients in shrimp feed on environmental performance for intensive farming. Fishmeal and squid meal were substituted with soybean meal, and fish oil with soy bean oil. Three scenarios were modeled: 10%, 30%, and 50% substitution (Figure S5, Supporting Information). After substitution, global warming would be 3−14% lower and biotic resource use would be 10−50% lower per metric ton of shrimp produced.

DISCUSSION

Although 85% of shrimp farms in China are currently semi-intensive[18] to serve domestic markets, the Chinese government subsidizes intensive farming for export to obtain foreign exchange earnings and promote economic development. The fraction of intensive farming has increased rapidly as a result.[4] However, expansion of export-oriented shrimp production can have negative environmental impacts.[4] As a result, two important questions arise: (1) Can export-oriented shrimp production be more sustainable? (2) How can more sustainable shrimp production be promoted?[4]

Comparison of Environmental Performance. With a total white-leg shrimp production of 1 270 000 t in 2008,[1] the estimated total greenhouse gas emissions from Chinese shrimp production would be 4 million metric tons, which was 0.06% of the energy-related CO_2 emissions for the entire country (6534 million metric tons).[19] The estimated total electricity and energy consumption for shrimp production would be 1.1 billion kW·h and 49 million GJ, 0.036% and 0.052% of the total electricity (3017 billion kW·h) and energy consumption (88.1 quadrillion Btus)[19] for the country.

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

Our results confirmed previous seafood LCA studies on shrimp and salmon that environmental impacts were concentrated at the production level, low for other subsystems, and negligible for infrastructure.[6,8] Following grow-out, processing also contributed substantially to total impacts. In contrast, hatchery and transportation to domestic markets made negligible contributions, which indicated that importing broodstock from Hawaii did not harm environmental performance. Distribution to Chicago port contributed a small but significant fraction to impacts of the intensive supply chain compared to grow-out and processing. Thus local or national consumption of fresh or frozen farmed shrimp without processing and packaging would reduce total environmental impacts substantially.

Strategies for Improving Environmental Performance. Activities that contributed disproportionately to the total environmental impacts during production were identified and could be used to develop regulation goals and mitigation measures to promote more sustainable shrimp production in the future. Feed production, electricity use, and pond effluents emerged as hotspots of concern for both farming systems. As one of the hotspots, shrimp feed currently used in China has been criticized for containing too much fishmeal and may potentially lead to depletion of marine fish resources. According to our analysis of shrimp feed production, fishmeal, followed by wheat flour, was the major contributor to all associated environmental impacts. Fish-derived ingredients generally are more impactful per unit mass basis compared to crop-derived ingredients.[8] Thus, substitution of fish-derived ingredients with crop-derived ingredients could be a good method to improve environmental performance and reduce associated impacts of shrimp feed. However, appropriate selection of substituted ingredients is critical, since some crop-derived ingredients such as wheat gluten meal are even more impact-intensive compared to some fish-derived ingredients such as menhaden meal.[11] Of course, substitutions must also be palatable to the shrimp and result in similar levels of growth and survival for this analysis to be legitimate. If substitution of fish-derived ingredients lowered shrimp production, the improvement of less impactful feed could be reduced or even outweighed by the higher amount of feed used.[8] Substitution with crop-derived ingredients could also induce new environmental problems such as deforestation due to soy cultivation[8] and exacerbation of eutrophication due to intensive fertilization requirement for wheat cultivation. Future research exploring alternative shrimp feed formulas should consider how to balance the above issues to achieve a win−win situation.

Shrimp feed conversion ratio is another pivotal environmental performance driver.[11] Our studied farming systems had an average FCR of 1.6 for intensive and 0.97 for semi-intensive farms. Since FCR is directly related to biotic resource use and nutrient retention, lower FCR reduces cumulative impacts of shrimp production. FCR is influenced mostly by feed composition, feeding management,[11] and feed quality such as stability in water. If feed composition was the same and feed remained stable longer in water, appropriate feeding regimes would reduce feed loss and dramatically lower FCR.

Electricity use was also identified as a hotspot of shrimp production for two reasons. First, high stocking density and feed inputs cause deteriorated water quality in shrimp farming systems. Frequent aeration and high water exchange rate, which consumed electricity, were required to maintain water quality. Second, the Chinese electricity-generating mix was coal-dominated.[20]To produce 1000 kW·h of electricity in China, a total of 889.7 kg of CO_2 equiv would be emitted.[20] Of that, 94.7% of the greenhouse gases were contributed by coal.[20] If China could change the current electricity mix toward less carbon-intensive energy production such as hydro, natural gas, or nuclear power, the impact of shrimp production on global warming would be reduced significantly. Even if cleaner energy sources are used, farmers should still adopt good aquaculture practices to minimize total energy use to achieve further improved environmental performance. Another solution would be installing renewable electricity technologies on-site, such as photovoltaics and wind turbines, if capital costs for small farms are not a barrier.

Farm-level nutrients released in pond effluents were another hotspot. Effluents primarily contain concentrated nutrients, organic matter, ammonia, and suspended solids derived from shrimp metabolites and uneaten food. It is the major contributor to eutrophication. Water quality depends mainly on farming system characteristics, feed quality, and management. As production intensifies, feed inputs and macronutrients retained in pond water also increase.[3] Usually about 22.7% of nitrogen and 10.6% of phosphorus inputs from shrimp feed are recovered in shrimp.[21] According to Jiang et al.,[22] 1 t live-weight of shrimp production in China can release 0.6 t of feces and 0.14 t of other metabolites. Moreover, our studied farms were outdoor flow-through systems that discharge effluents directly to receiving water bodies without treatment. To promote more sustainable shrimp farming, feeding regimes and stocking rates should be adjusted appropriately so as to not exceed the assimilation capacity of ponds. Policy makers should regulate shrimp farms to treat pond effluents before discharge, which would be necessary for sustainability and the reduction of environmental burdens. However, adopting effluent control could require more energy, and capital costs might be another barrier to adoption by small farms. Governmental intervention such as financial subsidies, tax exemptions, or market price regulation might overcome the capital barrier. Another solution would be shifting to closed recirculating systems to prevent eutrophication issues with discharge. When water was reused for salmon farming, the closed system outperformed open farming systems in eutrophication emission but all other environmental impact categories were substantially worse.[12] This was due to the increased input requirements for the recirculating system and lower unit production. There are potential advantages of closed recirculating systems such as less shrimp escapes and improved waste management. The use of suspended microbial floc systems in outdoor flow-though ponds could result in considerable reduction in life cycle impacts compared to indoor recirculating systems using mechanical water treatment. Any of these changes would require further evaluation of environmental performance and profitability to ensure more sustainable shrimp production.

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

Comparison of Life Cycle Impact Assessment Methodologies. There are numerous impact assessment methodologies developed in Simapro, such as CML 2000 and IMPACT 2002+.[17] Each method has a different focus that might lead to different results, thus making it difficult to determine which one to choose and which is most likely to approach the true estimation. According to ISO,[23] results from midpoint methodologies are more precise and detailed, while results from end-point methodologies are easier to understand and use for decision making. There is no single impact assessment methodology that could be applied to all food production systems.[6] We compared different LCIA methods by sensitivity analysis to evaluate the validity of our results. We found no discrepancies for the three most important impact categories for aquaculture. However, data available in the Simapro databases for aquaculture and fisheries products are very limited compared to other industrial products. Moreover, Chinese- or Asian-specific life cycle data are very limited in the Simapro databases, which contain data mainly from North America and Europe. Methods are still being developed for assessment of land use, water resources, and biodiversity loss, which limits the validity of our results in these important areas.[24]

Comparison with Other Fish or Agrifood Products. To put the impacts of shrimp production in perspective, we compared our results with other fish and agrifood products (Table S13, Supporting Information). Our results were specific to the shrimp case in China with semi-intensive and intensive culture systems, but these systems were also common in the many parts of the world. The specific impacts would differ in each location due to differences in factors such as electrical grid, but the general trend probably would be similar. However, due to differences in system boundaries, functional units, and impact assessment methodologies adopted, comparisons could be subjective.[7] On the basis of CO_2 emissions and energy consumption per kilogram of product produced, most products such as beef and pork are more GW-intensive and energy-intensive than fish products. Poultry is comparable to fish products in both impact categories, which confirms that poultry is among the most efficient land-based meat products.[13] Beef is the most GW-intensive and energy-intensive among all the food products, as it releases 9 times more greenhouse gases and consumes 7 times more energy compared to an equivalent amount of Chinese farmed shrimp. Among all fish products, Thai farmed shrimp was the most GW-intensive.[6] Farmed salmon is the most energy-intensive, as it requires twice the energy compared to an equivalent amount of Chinese farmed shrimp.[12] Tilapia is most efficient of all the food products in Table S13 (Supporting Information), probably due to its lower protein needs, higher FCR, and less or no need for aeration.[8]

ASSOCIATED CONTENT

Supporting Information. Thirteen tables and five figures with additional background information, life cycle inventory, and additional impact assessment results as described in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author
*E-mail: caoling@umich.edu.

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