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Resource Use Assessment of Shrimp, *Litopenaeus vannamei* and *Penaeus monodon*, Production in Thailand and Vietnam

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Abstract

Resource use was investigated at 34 *Litopenaeus vannamei* and five *Penaeus monodon* farms in Thailand and 30 *L. vannamei* and 24 *P. monodon* farms in Vietnam. Farms varied in water surface areas for production, reservoirs, canals, and settling basins; in pond size and depth; and in water management, stocking density, feeding rate, amendment input, aeration rate, crop duration, and crops per year. Production of *L. vannamei* averaged 17.3 and 10.9 m.t./ha/yr, and feed conversion ratio averaged 1.49 and 1.33 in Thailand and Vietnam, respectively. On average, production of 1 m.t. of *L. vannamei* required 0.58 ha land, 5,400 m^3 water, 60 GJ energy, and 1218 kg wildfish in Thailand and 1.76 ha land, 15,100 m^3 water, 33.7 GJ energy, and 1264 kg wildfish in Vietnam. Resource use per metric ton of shrimp declined with greater production intensity. In Thailand, *P. monodon* was produced at 0.2–0.4 m.t./ha/yr, with no inputs but water and postlarvae. In Vietnam, *P. monodon* production averaged 3.60 m.t./ha/yr. Production of 1 m.t. of *P. monodon* required 0.80 ha land, 36,000 m^3 water, 47.8 GJ energy, and 1180 kg wildfish, and resource use per ton production declined with increasing production intensity.

KEYWORDS

energy use, feed conversion efficiency, resource use, shrimp culture

Many capture fisheries are being exploited to their limit or beyond, and annual, global fisheries production has not exhibited a trend of increase since the early 1980s. Global aquaculture production has increased greatly, averting a shortage of fisheries products for the growing human population. The population is continuing to increase, and it is also becoming more affluent. The demand for fisheries products is expected to increase by at least 50% between now and 2050 (Boyd and McNevin 2015a). The entire future increase in demand for fisheries products must come from aquaculture, because capture fisheries are not expected to increase.

Aquaculture requires resources and can cause negative impacts such as land use modification, excessive water use, water pollution, exploitation of marine fisheries for fishmeal and oil included in feeds, and carbon emissions. These impacts can negatively affect terrestrial and

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aquatic biodiversity (Naylor et al. 1998, 2000, 2009; Diana 2009), and aquaculture must lessen its negative environmental impacts in order to assure a supply of fisheries products in the future.

Aquaculture typically is concentrated in specific areas where conditions are favorable for the construction of facilities and production of fish, shrimp, or other aquatic species. Thus, negative environmental impacts result from the combined effects of all facilities in an area. Moreover, aquaculture often is conducted in areas with multiple land and water uses, each of which contributes negative environmental impacts. This makes it difficult to separate environmental impacts among aquaculture facilities or to determine the proportion of negative impacts resulting from aquaculture. Boyd et al. (2015) suggested that resource use efficiency likely was the best indicator of responsible aquaculture. They based this conclusion on the premise that most negative environmental impacts result from resource acquisition and use.

The relationship of efficient resource use with responsible aquaculture can be illustrated using feed. Feed is a major input at many aquaculture production facilities. Although feed allows a great increase in aquaculture production, feeding waste is a major source of pollution. The production of feeds requires plant, fish, and animal byproduct meals and other ingredients. Many negative environmental impacts are associated with feed production (Boyd and McNevin 2015b; Chatvijitkul et al. 2016). By improving feed-use efficiency, resources are conserved and negative impacts – including those embodied in the feed – are lessened. In addition, feed is expensive, and greater feed-use efficiency lowers production costs.

An adequate instrument to understand and assess the impacts of the production of a specific product is life cycle analysis (LCA). This procedure assesses resource use and associated negative environmental impacts resulting from a product or service through its production, use, and final disposal – called the cradle-to-grave approach (Guinée 2002; Rebitzer et al. 2004; Horne et al. 2009). However, Jonell and Henriksson (2015) noted the magnitude of dispersions underpinning LCA results, indicating limited accuracy even for relatively assertive impact categories. LCA studies are most useful for macro-level assessments to determine where major areas of impact (hotspots) are within the supply chain of a particular product. In aquaculture, inputs and resulting negative impacts for production of the same species by a single basic culture technique vary greatly among farms as demonstrated for pond culture of channel catfish, *Ictalurus punctatus* (Boyd et al. 2000). Further, production practices change over time, requiring a continuous body of research from which LCA assumptions can be drawn. Several LCA studies have been performed for a variety of aquaculture species: some examples are Mungkung et al. (2006); Papatryphon et al. (2004); Pelletier et al. (2009); Pelletier and Tyedmers (2010); Cao et al. (2011); Jonell and Henriksson (2015). This research illustrated that natural resource use and negative impacts were concentrated at the farm level and that considerable resources were embodied in inputs, especially in feed.

In order to improve resource use and lessen negative impacts of aquaculture, reliable data are needed on farm infrastructure, operational procedures, inputs, and production across a wide range of farms of major aquaculture species. Several surveys of resource use in shrimp farming have been conducted in addition to LCA efforts mentioned earlier. These include Henriksson et al. (2014) (http://www.media.leidenuniv.nl/legacy/d35-final-case-study-report.pdf), Jahan et al. (2015), Gräslund et al. (2003), Yuvanatemiya et al. (2011), Global Aquaculture Alliance (2006), and many reports prepared by the World Bank, Network of Aquaculture Centres in Asia-Pacific, World Wildlife Fund, and Food and Agriculture Organization of the United Nations Consortium Program on Shrimp Farming and the Environment in the early 2000s (http://www.library.enaca.org/Shrimp/Publications/DraftSynthesisReport-21-June.pdf).

Data from these sources contain much information pertinent to recommendations for resource efficient – and presumably more "environmentally responsible" – shrimp production methods.

Aquaculture certification programs currently have many standards that must be audited for compliance, but these standards are not prioritized well with respect to importance in environmental protection (Boyd and McNevin 2016a, 2016b). It has been suggested that LCA could be used as a tool for identifying practices most relevant for use in certification audits (Jonell and Henriksson 2015). Although this is a logical suggestion, the use of LCA as an auditing tool in itself would be even more complex than current certification auditing of standards and practices. Thus, Boyd et al. (2015) suggested the use of seven indicators (land use, water use, energy use, feed conversion ratio [FCR], survival, wildfish included in feed, and dissolved oxygen concentration in receiving water bodies) as surrogates for many of the standards in aquaculture certification programs. Many of these indicators (land use, water use, feed use, energy use, and wildfish included in feed) have been isolated as major impacts in previous LCAs mentioned earlier. Use of these indicators would cause certification efforts to focus mainly on major impacts to simplify auditing and lessen the cost of audits.

This study was conducted to assess production practices across a sample of shrimp farms in Thailand and Vietnam and to determine performance with respect to indicators suggested by Boyd et al. (2015).

Materials and Methods

It was intended initially to select farms randomly from satellite imagery, but many farmers, especially in Thailand, refused to participate in interviews. Therefore, several major shrimp farming provinces in each country were chosen. Areas in each province that appeared to contain farms of different sizes and operate at different production intensities (based on number of aerators visible in images) were identified from satellite imagery. The interview teams went to these areas and selected possible farms in proportion to the percentage of extensive, semi-intensive, and intensive shrimp culture thought to occur in each country. Farms were selected based on the willingness of owners and managers to participate in the survey. We believe that the reluctance of farmers to participate involved two factors. The interviews and farm inspections were time consuming, requiring nearly an entire day at most farms, and up to 2 d at larger farms. Moreover, an international, environmental nongovernmental organization was conducting the survey, and the farmers were suspicious of the project motives. As a result, the number of participating farms was considerably lower than in earlier surveys in Thailand and Vietnam (Henriksson et al. 2014) and in Bangladesh (Jahan et al. 2015). The farms were not – as explained earlier – selected completely at random. But the interviews provided data on specific items required for revealing differences in farming and management practices for assessing the targeted indicators.

The survey included 34 farms for whiteleg shrimp, *Litopenaeus vannamei*, and five farms for black tiger shrimp, *Penaeus monodon,* in Thailand and 28 farms for whiteleg shrimp and 24 farms for black tiger shrimp in Vietnam. Heterotrophic, biofloc, culture systems (Avnimelech 2015) were not included in the survey as this method does not constitute a large share of

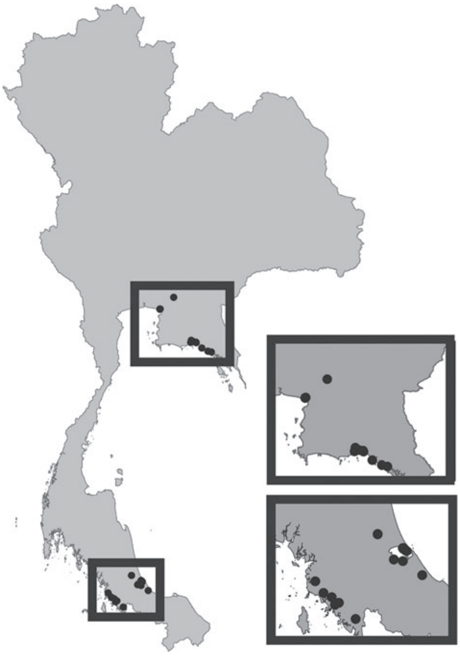

FIGURE 1. *Locations of sampling areas in Thailand.*

shrimp production in either country. In Thailand (Fig. 1), farms for *L. vannamei* were located in the following provinces: Chachoengsao ($n = 1$), Chantaburi ($n = 3$), Pattalung ($n = 2$), Rayong ($n = 11$), Satun ($n = 6$), and Songkhla ($n = 11$). All five *P. monodon* farms in Thailand were in Chachoengsao province. The farms in Vietnam (Fig. 2) were in the three major shrimp farming provinces, and the number of ponds for *L. vannamei* and *P. monodon* production were, respectively: Bac Lieu ($n = 7$ and 7); Cau Mau ($n = 10$ and 4); and Soc Trang ($n = 13$ and 13).

A survey instrument was used by the interviewers in an effort to assure consistency of interviews. Native speakers experienced in shrimp farming techniques and environmental issues were trained to use the queries in the survey instrument to conduct interviews with farm owners and to examine farm records and infrastructure. There were 103 queries, and only the main features of the survey instrument are summarized in Table 1. Queries about several key issues were asked in two or more forms to allow answers to be cross-checked for reliability.

The entire farm areas were considered to be used for shrimp culture, because only few farms produced other crops – just some extensive farms in which other species were stocked with shrimp. There were many instances where farms reported complete mortality of shrimp in some ponds. Sometimes ponds were restocked and in other instances no crop was produced. Lacking reliable information on percentage of crop failures, production estimates were based on performance of entire farms.

FIGURE 2. *Locations of sampling areas in Vietnam.*

TABLE 1. *List of the main types of information obtained during farm visits and interviews with farm owners.*

Species produced
Water surface areas and depths of reservoirs, canals, production, and sedimentation basins
Total area of farm devoted to shrimp production
Water management details
Pond and water preparation details
Stocking rate
Amount of aeration and hours of aerator operation
Amendments applied to ponds (types, rates, and frequencies)
Total feed input
Days in crop and number of crops per year
Survival and production
Total electricity use
Total use of other fuels

Production at each farm was estimated in three ways as follows:

$$P_p = \frac{H_a}{A_p} \tag{1}$$

$$P_f = \frac{H_a}{A_f} \tag{2}$$

$$P_b = \frac{A_f + L_e}{H_a} \tag{3}$$

where P_p is pond production based on total production pond water surface area (m.t./ha/yr), P_f is farm production based on entire farm area (m.t./ha/yr), P_b is land burden for shrimp production based on shrimp farm land plus crop land embodied in feed ingredients (ha/m.t./yr), H_a is total shrimp production by farm (m.t./yr), A_p is production pond surface area (ha), A_f is shrimp farm area (ha), and L_e is land area embodied in feed (ha).

The FCR for each farm was estimated as follows:

$$\mathrm{FCR} = \frac{F}{H_a} \tag{4}$$

TABLE 2. *Direct and embodied energy coefficients.*

Variable	Quantity	Direct energy (GJ)	Land (ha/m.t.)	Embodied resources in feed[1] Water (m^3/m.t.)	Energy (GJ/m.t.)	Wildfish(kg/m.t.)
Electricity	1 kWh	0.0036	–	–	–	–
Diesel fuel	1 L	0.0387	–	–	–	–
Feed						
Litopenaeus vannamei	1 t	–	0.249	112	9.07	818
Penaeus monodon	1 t	–	0.232	113	10.64	1302

[1] Chatvijitkul et al. (2016).

where F is the amount of feed purchased annually by farm (m.t./yr).

Most farms did not exchange water with outside water bodies during the crop production, but many exchanged water with a farm reservoir. At harvest, ponds were drained to the outside, but the entire system usually was drained only once per year. Rainfall into and evaporation plus seepage out of ponds in the shrimp culture areas of both countries are approximately equal on an annual basis (Yoo and Boyd 1994; Nghi et al. 2008). Runoff into ponds was considered negligible, because only the above water, inside slopes of embankments, drained into production ponds. Direct water use was calculated by the equation:

$$W_d = \frac{\left[V_s + \left(V_p \times n\right)\right] + \left[V_p \left(W_x/100\right)(D)(n)\right]}{P_a} \tag{5}$$

where W_d is direct farm water use (m^3/m.t.); V_s is combined volume of reservoirs, canals, and production ponds (m^3); V_p is volume of production ponds (m^3); W_x is daily water exchange rate with outside (% pond volume/d); $D =$ d/crop; and $n =$ crops/yr. Direct farm water use was approximately equal to the volume of water discharged by a farm.

Fuel use for farm construction and pond repair was obtained in interviews with pond construction contractors in both countries. Typical diesel fuel use for construction was 5000 L/ha/m depth, while the typical renovation required was 4500 L/ha. Intensive ponds usually were renovated once about every 5 yr, while extensive ponds usually were renovated after about 15 yr. For purposes of this study, a pond service life of 30 yr was assumed, although most ponds can be used longer if properly maintained. Total energy use for construction and renovation was calculated as follows:

$$E_c = \frac{\left[(5000)\left(A_r D_r + A_c D_c + A_p D_p + A_s D_s\right) + (4500)\left(A_w\right)(n)\right] C_d}{30\, P_a} \tag{6}$$

where E_c is energy for construction and renovation (GJ/m.t.); A is area (ha); D is depth (m); subscripts r, c, p, s, and w correspond to reservoir, canal, production pond, settling basin, and farm water surface, respectively; C_d is energy coefficient of diesel fuel (GJ/L) (Table 2).

Operational fuel use (all farms used diesel fuel) and electricity use allowed estimates of operational energy. The equation was:

$$E_o = \frac{V_d C_d + K C_k}{P_a} \tag{7}$$

where E_o is operational energy (GJ/m.t.), V_d is volume diesel fuel (L), K is electricity use (kWh), and C_k is energy coefficient for electricity (Table 2).

Embodied land, water, energy, and wildfish in feed were determined by the following equations:

$$L_e = \frac{F \times C_l}{H_a} \tag{8}$$

$$W_e = \frac{F \times C_w}{H_a} \tag{9}$$

$$E_e = \frac{F \times C_e}{H_a} \tag{10}$$

$$WF_e = \frac{F \times C_{wf}}{H_a} \tag{11}$$

TABLE 3. *Means and SEs for land use (in hectares) at shrimp farms in Thailand and Vietnam.*

Land use	Thailand ($n = 34$)	Vietnam *Litopenaeus vannamei* ($n = 28$)	Vietnam *Penaeus monodon* ($n = 24$)
Total farm area	14.76 ± 3.13	3.46 ± 0.81	2.11 ± 0.29
Reservoirs	4.75 ± 2.04	0.31 ± 0.06	0.21 ± 0.04
Canals	0.34 ± 0.15	0.16 ± 0.06	0.17 ± 0.07
Production ponds	6.96 ± 1.36	1.76 ± 0.61	1.18 ± 0.22
Sedimentation basins	0.86 ± 0.24	0.09 ± 0.05	0.02 ± 0.02
Embankments, staging area, and so on	1.85 ± 0.58	0.67 ± 0.39	0.38 ± 0.23

where L_e, W_e, E_e, and WF_e are embodied land (ha/m.t.), water (m^3/m.t.), energy (GJ/m.t.) and wildfish in feed (kg/m.t.), respectively; F = annual feed use (m.t.); and C_l, C_w, C_e, and C_{wf} are embodied resource use coefficients for land, water, energy, and wildfish (taken from Chatvijitkul et al. 2016), respectively (Table 2).

Data were analyzed through use of averages and SEs, histograms, and regression analyses. Statistical analyses were performed using SAS version 9.4 statistical software (SAS Institute, Inc., Cary, NC, USA).

Results

Litopenaeus vannamei

Farms and Ponds. Averages and SEs for total farm areas and areas of reservoirs, canals, production ponds, and settling basins are given in Table 3. Most of the land area of each farm was devoted to water surface area of ponds, reservoirs, canals, and settling basins; the averages were 82.7 ± 17.4% in Thailand and 82.0 ± 18.0% in Vietnam. Farms in Thailand ranged from less than 1 ha to nearly 30 ha in production water surface area, and there were 14 farms with more than 10 ha in production. In Vietnam, farms tended to be smaller; only two farms had more than 3 ha in production. Average production area was 6.96 ± 1.36 ha/farm in Thailand, but only 1.76 ± 0.61 ha/farm in Vietnam. The production area ranged from around 20% to about 92% (average = 47.2 ± 12.5%) of farm area in Thailand and from about 10% to nearly 80% (average = 50.9 ± 3.4%) in Vietnam.

The size and depth of production ponds also tended to be greater in Thailand than in Vietnam. Ponds were 0.4–1.25 ha (average = 0.65 ± 0.04 ha) in Thailand and from 0.10–0.68 ha (average = 0.33 ± 0.03 ha) in Vietnam. Average depths ranged from 1.05 to 2.00 m (overall average = 1.52 ± 0.04 m) and from 0.95 to 1.95 m (overall average = 1.34 ± 0.18 m) in Thailand and Vietnam, respectively.

All but two farms in Thailand and three in Vietnam had reservoirs for treating water before introducing it into production ponds and for use in internal water exchange during the crop production. Reservoirs in Thailand ranged from less than 10% to nearly 140% of production area with an average of 68.2 ± 6.1% of production area. A wide range in relative reservoir area also was found in Vietnam; it averaged only 17.6 ± 7.2%. Reservoirs allow water to be treated with disinfectants before introduction into ponds, provide time for free shrimp viral particles in water to deactivate, permit coarse suspended solids to precipitate, serve as a supply water to replace seepage and evaporation from production ponds, and allow internal exchange of water with ponds during the crop production.

Sedimentation basins allow coarse solids to settle from farm effluents before they are discharged into natural waters, providing a degree of water quality protection. In Thailand, only six farms lacked sedimentation basins, while in Vietnam 20 farms operated without sedimentation basins. The average sedimentation area in Thailand was 12.4 ± 3.7% of the production area, but it was 7.7 ± 3.3% in Vietnam.

In Thailand, 16 of the 34 farms covered the inside surfaces of embankments of production ponds with high-density polyethylene liners to avoid erosion by aerator-generated water currents. Liners protect embankments, and they also lessen total suspended solid concentrations in pond waters and effluents (Saengrungruang and Boyd 2014). None of the farms in Vietnam applied liners to embankments.

Operational Inputs. Farms in both countries allowed pond bottoms to dryout for 2 wk or more between crops as a means of destroying disease organisms and their vectors that might persist from the previous crop. Burnt lime (CaO) often was added to pond bottoms during dry-out to raise pH for the purpose of destroying disease organisms (Table 4); 13 farms in Thailand and 28 farms in Vietnam applied lime during pond preparation. Several farms in both countries also applied agricultural limestone to ponds (Table 4) to neutralize soil acidity, and in a few cases, both lime and agricultural limestone were applied.

Disinfectants were applied to reservoirs before filling ponds or directly to ponds before stocking as a precaution against possible introduction of disease organisms. Calcium hypochlorite ($Ca[OCl]_2$) or a combination of calcium hypochlorite and copper sulfate ($CuSO_4 \cdot 5H_2O$) were the most common disinfectants in Thailand, but potassium permanganate, providone iodine, and benzalkonium chloride (BKC) also were used (Table 4). In Vietnam, the most common disinfectants were calcium hypochlorite and providone iodine, and some farms used potassium permanganate ($KMnO_4$), copper sulfate, hydrogen peroxide (H_2O_2), BKC, glutaraldehyde, or Virkon® (Virkon Disinfectant Technologies, Sudbury, Suffolk, UK).

The piscicide saponin (from teaseed cake) was applied to ponds to destroy wildfish before stocking postlarvae at nine farms in Thailand and six farms in Vietnam (Table 4). The disinfectants applied to ponds also served as piscicides.

Stocking densities ranged from about 30 to 120 postlarvae/m^2 (average $= 76.5 \pm 6.8/m^2$) in Thailand and from around 10 to 110 postlarvae/m^2 (average $= 57.3 \pm 5.1/m^2$) in Vietnam. After stocking, shrimp at all farms in both countries were provided feed daily. The feed typically contained 35–38% crude protein, and it usually was applied five times daily.

TABLE 4. *Amendments and amounts (means ± SEs) used in ponds for* Litopenaeus vannamei *at 34 farms in Thailand and 28 farms in Vietnam.*[1]

	Thailand		Vietnam	
Amendment	*n*	Amount	*n*	Amount
Lime	13	3802 ± 1146	26	1966 ± 213
Agricultural limestone	17	5265 ± 1277	12	1377 ± 258
Sodium bicarbonate	2	602	0	–
Calcium hypochlorite	19	688 ± 100	10	342 ± 56
Potassium permanganate	7	251 ± 52	1	200
Copper sulfate	15	289 ± 35	1	60
Hydrogen peroxide*	0	–	1	1500
Iodine*	2	106	16	26 ± 7
Benzalkonium chloride*	4	78 ± 11	7	34 ± 14
Glutaraldehyde*	0	–	2	75
Virkon*	0	–	1	5
Brown sugar or molasses	12	1151 ± 177	0	–
Saponin	9	931 ± 120	6	292 ± 79
Yucca	0	–	5	8.3 ± 2.3
Zeolite	2	1762	17	856 ± 135
Mineral mix	17	?	6	267 ± 98
Urea	1	35	0	–
Triple superphosphate	0	–	1	100
Mixed fertilizer[2]	2	48	1	100
Cow manure	1	?	0	–
Chicken manure	1	?	0	–
Probiotics	34	?	28	?
Antibiotics	0	–	10	?
Vitamin C	?	?	8	?
Sorbitol	0	–	1	?

[1] Amounts are in kilograms per hectare annually (kg/ha/yr) except where noted by asterisk (L/ha/yr).

[2] Contains nitrogen, phosphorus, and potassium.

Mechanical aeration was used – except for one farm in Thailand and three farms in Vietnam – to avoid low dissolved oxygen concentration. Aeration was almost exclusively by long-arm aerators (Fig. 3A) or floating, electric paddlewheel aerators (Fig. 3B). The total horsepower of motors used for driving aerators averaged almost twice as great in Thailand as in Vietnam – 43 ± 4 hp/ha versus 24 ± 3 hp/ha (Fig. 4). Farms in Thailand also tended to operate aerators more hours per day than did farms in Vietnam. The largest class interval for aeration time was 18–24 h in Thailand and 12–18 h in Vietnam.

Molasses or brown sugar was used to ferment probiotics applied at all farms in Thailand, because farmers believe that these products improved water quality. However, at 12 farms, molasses or brown sugar also was applied directly to the water (Table 4). Farmers believed

FIGURE 3. *Left: Long-arm paddlewheel aerator. Right: Floating electric paddlewheel aerator.*

that this treatment stimulated development of favorable microbial communities that were less likely to contain species pathogenic to shrimp. All farms in Vietnam also used probiotics, but molasses and brown sugar were not used to ferment probiotics or applied directly to ponds. Most farms in Thailand and some farms in Vietnam also applied small quantities of lime or agricultural limestone to ponds at 3- to 7-d intervals for the purpose of maintaining a stable pH – many farmers believed that shrimp are less susceptible to disease if pH is between 7.8 and 8.2.

Zeolite was applied to only two farms in Thailand, but 17 farms in Vietnam treated ponds regularly with this cation exchange agent, because vendors claim that it removes ammonia from pond water. Five farms in Vietnam also applied an extract of the *Yucca* plant that is claimed by vendors to remove ammonia from water (Table 4).

In Thailand, half of the farms applied minerals (Table 4) consisting of various combinations of calcium chloride ($CaCl_2 \cdot 2H_2O$), calcium sulfate ($CaSO_4 \cdot 2H_2O$), magnesium chloride ($MgCl_2$), magnesium sulfate ($MgSO_4 \cdot 7H_2O$), potassium chloride (KCl), potassium sulfate (K_2SO_4), sodium chloride (NaCl), and sodium carbonate (Na_2CO_3) to ponds. Six farms in Vietnam used a mineral mix containing calcium, magnesium, and potassium salts. Minerals are applied for the purpose of encouraging a satisfactory balance of major ions in pond water.

There was little application of fertilizers to ponds in both countries. Three farms in Thailand applied inorganic fertilizers and two applied animal manures. Two farms in Vietnam used inorganic fertilizer (Table 4). Other amendments included antibiotics (Vietnam only), vitamin C treatment of feed, and sorbitol (Table 4).

Production Data. In Thailand and Vietnam, most farms – 64.7% and 70%, respectively – produced two crops per year. A few farms produced only one crop per year – mostly in Vietnam – while a few farms in both countries produced up to three crops per year. The duration of crops varied greatly (especially in Vietnam), but the average crop duration was around 90 d in both countries.

The annual production of farms varied greatly because of variation in farm production area, stocking density, crop duration, and crops per year. The largest class interval for annual farm production in Thailand was $\leq$50 m.t./yr/farm, while in Vietnam, the largest class interval was $\leq$5 m.t./yr/farm (Fig. 5). A few farms in both countries produced over 100 m.t./yr; average annual production was 103.8 ± 23.1 m.t./yr in Thailand and 26.2 ± 14.1 m.t./yr in Vietnam.

Pond production intensity based on water surface area ranged from less than 5 m.t./ha/yr to nearly 40 m.t./ha/yr in both countries, but the average was considerably more in Thailand (17.7 ± 2.0 m.t./ha/yr) than in Vietnam (9.3 ± 1.9 m.t./ha/yr) (Fig. 5). Farms that

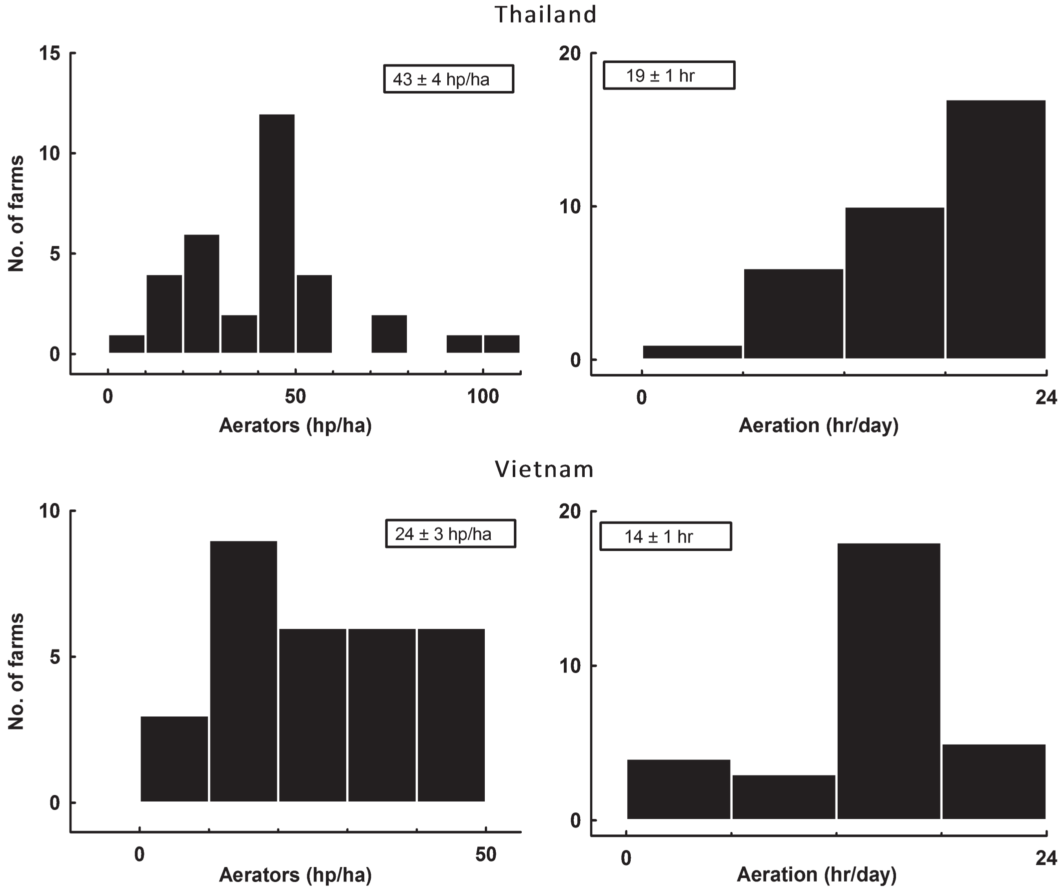

FIGURE 4. *Horsepower of aeration per hectare and number of hours of aeration per day at* Litopenaeus vannamei *farms in Thailand and Vietnam. Averages and SEs are in boxes.*

produced more crops per year tended to have the greatest production intensity. In Thailand, farms reporting 1.5–2.0 crops/yr had average pond production intensity of 12.3 ± 2.0 m.t./ha/yr as compared with 29.5 ± 2.9 m.t./ha/yr for farms reporting 2.5–3.0 crops/yr. In Vietnam, farms with one or two crops per year had average pond production intensities of 6.5 ± 1.8 and 9.1 ± 2.2 m.t./ha/yr, respectively, while average production was 26.0 ± 5.1 m.t./ha/yr for farms reporting three crops per year.

Farmers reported average survival of shrimp from stocking to harvest of 73.9 ± 1.7% in Thailand and 70.8 ± 4.4% in Vietnam. However, no farms in Thailand reported survival below 50%, while four farms in Vietnam attested to lower than 50% survival. Failed crops reported by some farms in both countries were not included in the survival estimates. Hence, the actual survival of postlarvae to harvest at some farms is more or less than reported earlier for successful crops.

The FCR was highly variable among farms in both countries, ranging from about 1 to 2, but average FCR was similar – 1.33 ± 0.40 in Vietnam versus 1.49 ± 0.23 in Thailand. The FCR was based on annual feed purchases, and feed added to ponds in which crops failed was included in estimates of farm FCR (Eq. 4).

Major Resource Use. Production area expressed as a percentage of total farm area ranged from about 25 to 90% in Thailand (average = 47.2 ± 12.5%) and from around 15

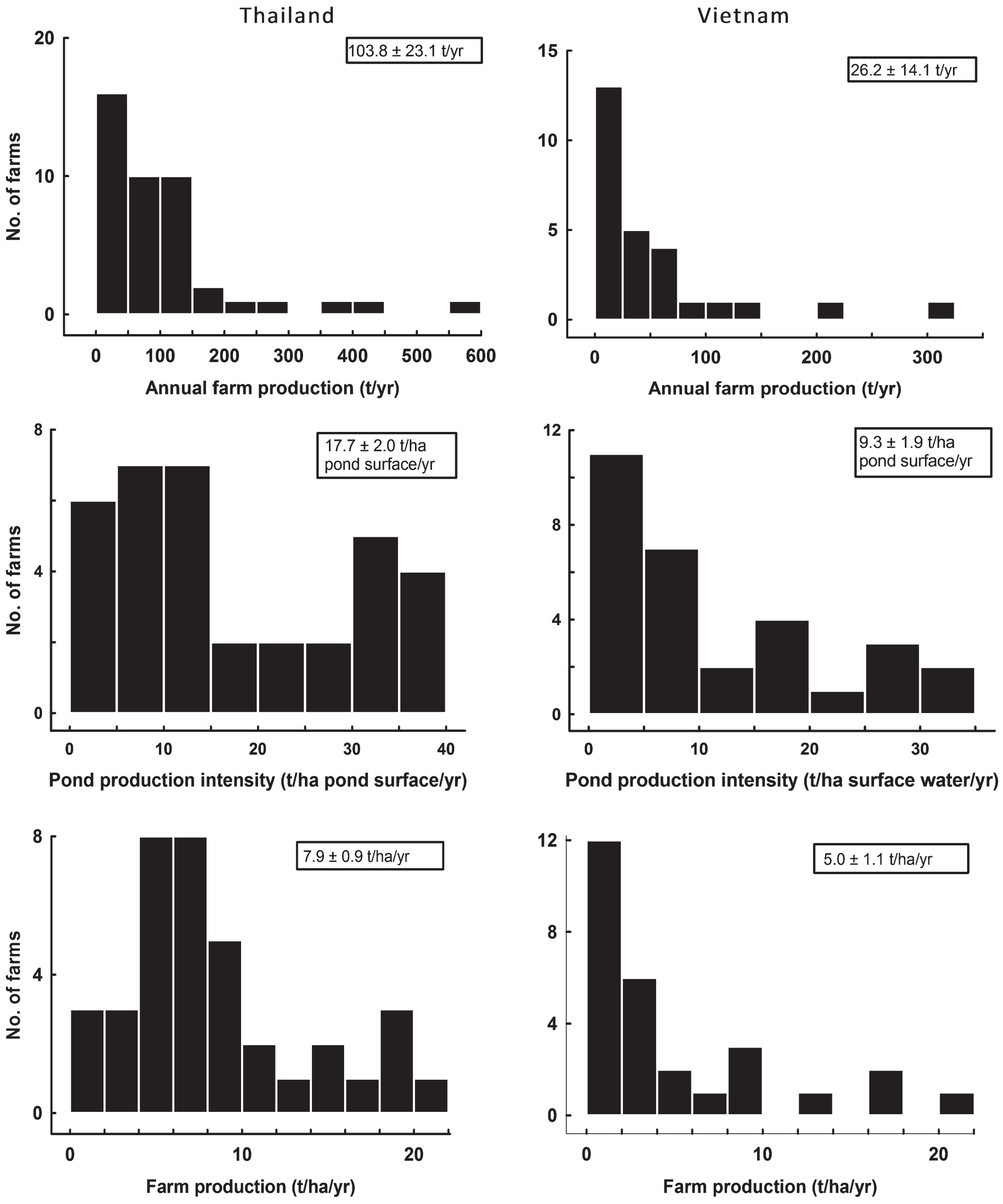

FIGURE 5. *Total annual farm production, pond production intensity, and farm production intensity at* Litopenaeus vannamei *farms in Thailand and Vietnam. Averages and SEs are in boxes.*

to 75% in Vietnam (average = 50.9 ± 3.4%). Each hectare of production area at shrimp farms in Thailand had an additional 1.08 ha land for reservoirs, canals, sedimentation basins, and other purposes (Table 3). In Vietnam, the support area for 1 ha was 1.07 ha. Based on total farm area (farm production intensity), farms in Thailand produced an average of 7.8 ± 0.9 m.t./ha/yr, while farms in Vietnam averaged 5.0 ± 1.1 m.t./ha/yr (Fig. 5).

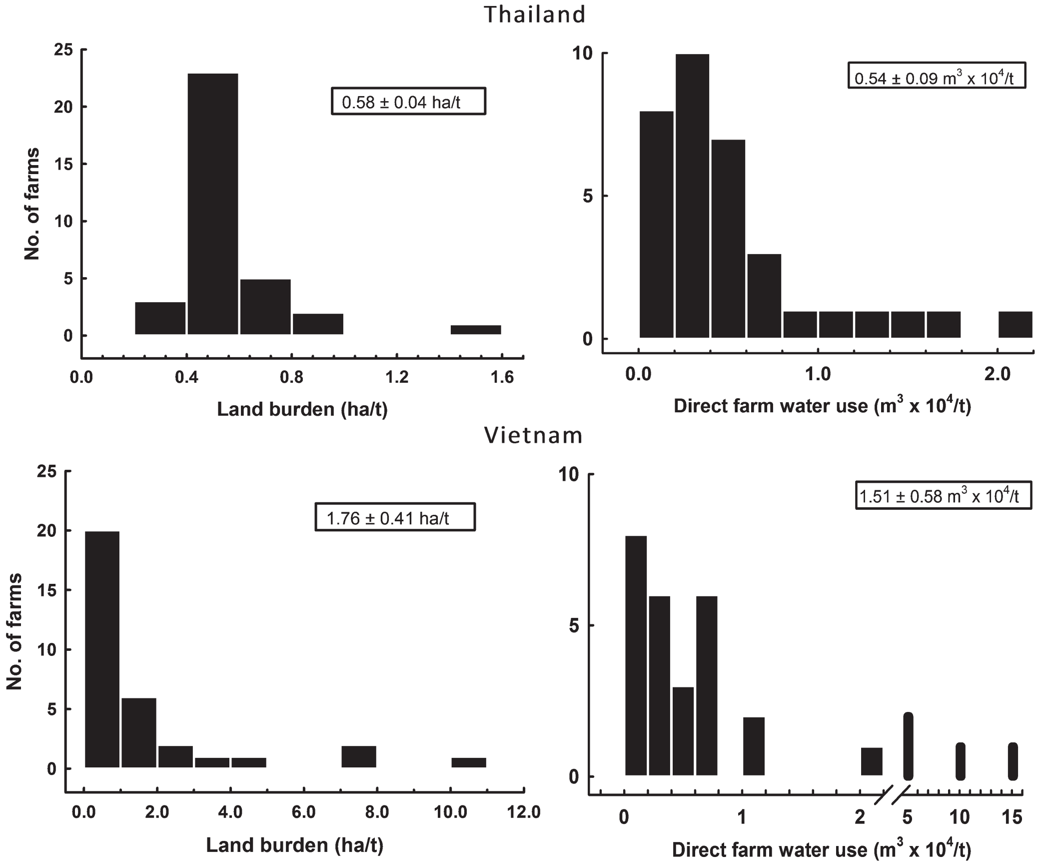

FIGURE 6. *Total land burden and direct farm water use at* Litopenaeus vannamei *farms in Thailand and Vietnam. Averages and SEs are in boxes.*

The land burden values for pond production and farm production in Thailand and Vietnam were 0.06 and 0.09 ha/m.t. and 0.21 and 1.38 ha/m.t., respectively. However, when embodied land in feed was combined with total shrimp farm land, the total land burden averaged 0.58 ± 0.04 ha/m.t. in Thailand and 1.76 ± 0.41 ha/m.t. in Vietnam (Fig. 6). The major land use for shrimp aquaculture in Thailand was agricultural land necessary to produce plant-based feed ingredients, while in Vietnam, shrimp farm area was greater than land necessary for feed ingredients.

Direct farm water use at most farms in both countries was less than 10,000 m^3/m.t. (Fig. 6). However, on average, Thai shrimp culture used only about one third as much water per ton of shrimp as did Vietnamese shrimp culture. This resulted because production was lower in Vietnam than in Thailand, and some farms in Vietnam exchanged water with outside sources.

Much energy was necessary for construction and repair of ponds and other earthen, farm infrastructure (Fig. 7). The large variation in energy for construction and repair among farms resulted from differences in pond depth, areas of canals, reservoirs, and settling basins relative to production area, and intensity of production. Based on data in Table 3, to construct the average farm in Thailand (6.96 ha production area; 4.75 ha reservoir; 0.86 ha of sedimentation basin; 0.34 ha canals; 1.5 m deep) would require 96,825 L diesel fuel (3747 GJ equivalent) or 538 GJ/ha of production area. The energy requirement to construct a typical farm in Vietnam (1.76 ha production area; 0.21 ha

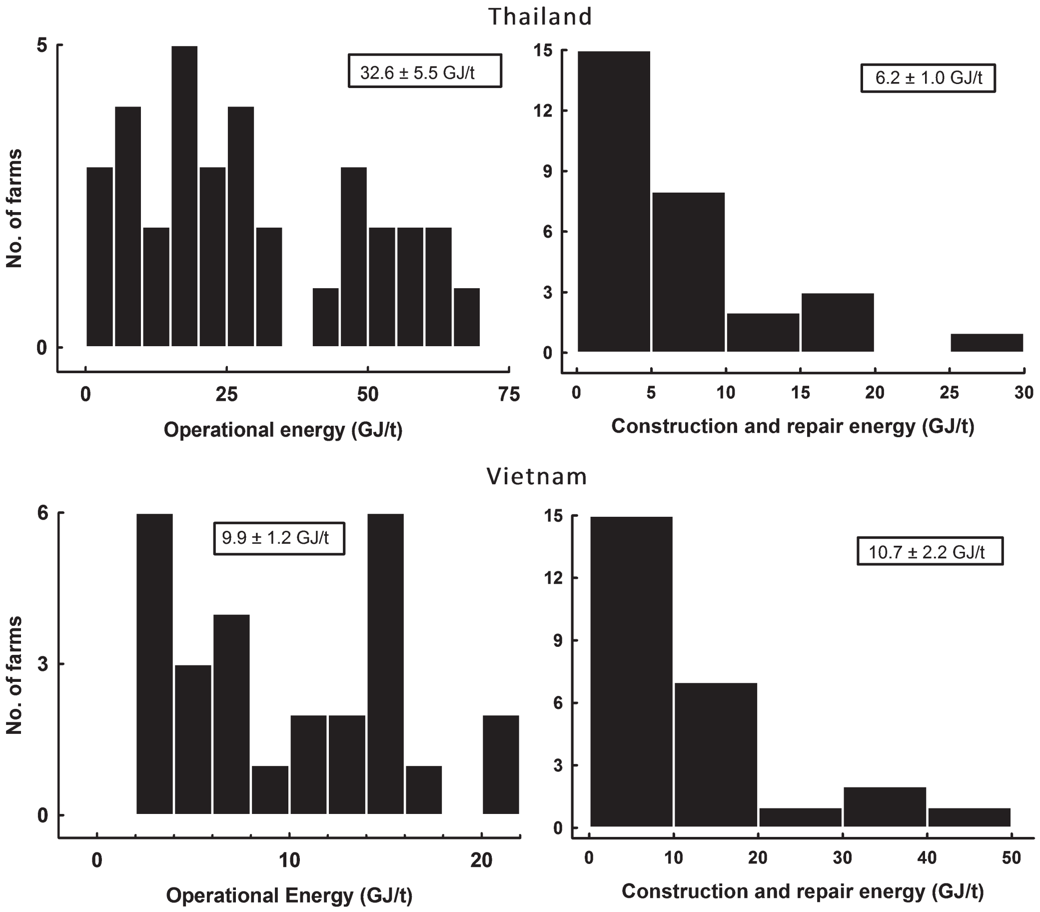

FIGURE 7. *Energy use for farm earthwork construction and repair and for operational energy at* Litopenaeus vannamei *farms in Thailand and Vietnam. Averages and SEs are in boxes.*

reservoirs; 0.17 ha canals; 0.02 ha sedimentation basin; 1.34 m deep) would be 342 GJ/ha of production area. The difference in construction energy between the two countries resulted from less reservoir and sedimentation area and slightly shallower ponds in Vietnam than in Thailand. Over time, the energy requirement for cleaning and repairing ponds will exceed the initial construction energy input. The construction and repair energy requirement amortized over 30 yr and converted to a 1 m.t. of shrimp basis averaged 6.2 ± 1.0 GJ/m.t. and 10.7 ± 2.2 GJ/m.t. in Vietnam and Thailand, respectively.

Operational energy ranged from about 2 GJ/m.t. to nearly 164 GJ/m.t., with an average of 32.6 ± 5.5 GJ/m.t. in Thailand. In Vietnam, operational energy did not exceed 28 GJ/m.t., and the average was 9.9 ± 1.2 GJ/m.t. (Fig. 7). Energy for pumping water, cleaning pond bottoms between crops, and removing sediment from sedimentation basins was mostly from diesel fuel, while electricity was used mainly for aeration. The ratio of electrical energy : diesel fuel energy was 16.5 in Thailand and 20.3 in Vietnam. Thus, the greatest operational energy was for aeration in both countries. Operational energy exceeded construction energy in both countries, but especially in Thailand, because of greater energy use for aeration.

Average energy use (construction and repair + operational + embodied in feed) for shrimp production was 51.0 ± 5.9 GJ/m.t. in Thailand and 33.7 ± 3.6 GJ/m.t. in Vietnam. Operational energy exceeded combined energy

TABLE 5. *Means ± SEs for embodied land, water, energy, and wildfish in feed to produce 1 m.t. of* Litopenaeus vannamei *at farms in Thailand and Vietnam.*[1]

Resource	Thailand ($n = 34$)[1]	Vietnam ($n = 28$)[1]
Land (ha/m.t.)	0.365 ± 0.010	0.323 ± 0.024
Water (m^3/m.t.)	1640 ± 58	1520 ± 9
Energy (GJ/m.t.)	11.92 ± 0.33	10.92 ± 0.66
Wildfish (kg/m.t.)	1210 ± 34	1090 ± 64

[1] There were no differences between means as determined by *t*-test at $P = 0.05$ (horizontal comparisons only).

for construction and repair of farm earthen infrastructure and feed ingredient production in Thailand, but not in Vietnam where embodied energy in feed ingredients was roughly equal to operational energy.

Embodied resources in feed varied directly with FCR, and means and SEs are presented (Table 5). Numerical values for embodied land, water, energy, and wildfish were slightly higher for Thailand than for Vietnam, because the same was true for FCR. In Thailand, three farms had a fish-in : fish-out ratio below 1.0, while 14 farms in Vietnam had a ratio below 1.0. However, there were no differences between means for wildfish use or other embodied variables at $P = 0.05$. The estimates for the two countries were combined, giving the following estimates of embodied resources in feed for *L. vannamei* production: land, 1.17 ha/m.t.; water, 1.44 m^3/m.t.; energy, 46.8 GJ/m.t.; and wildfish, 1241 kg/m.t. (fish-in : fish-out ratio = 1.24).

Penaeus monodon

Farms and Ponds. Farms for *P. monodon* in Thailand were operated for extensive production with water supplied by tidal action and no inputs to ponds other than stocking of postlarvae and application of probiotics. These five farms ranged from 4.8 to 16 ha in water surface area and the total land burden for production ranged from 2.5 to 5 ha/m.t./yr.

Farming of *P. monodon* was more common in Vietnam than in Thailand, and it was possible to include farms operated at different production levels in the survey. Average farm areas and areas for reservoirs, canals, production, sedimentation basins, and supporting areas are provided (Table 3). Production areas on farms ranged from less than 0.5 ha to nearly 4.5 ha and averaged 1.16 ± 0.24 ha. Ponds ranged from less than 0.1 ha to 1.0 ha with an average area of 0.33 ± 0.05 ha each. Pond depth varied from less than 0.2 m to nearly 2.0 m with an average of 1.17 ± 0.07 m depth. Reservoirs were not used at six farms, but at other farms, reservoirs were between 5 and 100% of production area – average of 17.8 ± 5.1%. Only two farms had sedimentation basins, and plastic liners were not used in production ponds to avoid erosion by aerators.

Operational Inputs. Ponds for *P. monodon* were dried between crops for sanitation in the same manner as described for *L. vannamei* culture. Most ponds also were treated with lime, agricultural limestone, or both during pond preparation (Table 6). Disinfectants were used; calcium hypochlorite, providone iodine, BKC, or some combination of these three chemicals was most commonly applied as disinfectants (Table 6). In addition, some farms applied saponin to

TABLE 6. *Amendments and amounts (means ± SEs) used in ponds at 24* Penaeus monodon *farms in Vietnam.*[1]

Amendment	*n*	Amount
Lime	13	1108 ± 213
Agricultural limestone	13	1275 ± 281
Calcium hypochlorite	6	128 ± 56
Iodine*	10	10 ± 3
Benzalkonium chloride*	5	70 ± 25
Trichloroisocyanuric acid*	1	90
Molasses	1	231
Saponin	6	184 ± 88
*Yucca**	1	46
Zeolite	10	624 ± 208
Mineral mix	3	96 ± 45
Triple superphosphate	1	66
Diammonium phosphate	2	98
Mixed fertilizer[2]	5	100 ± 5
Probiotics	24	?
Antibiotics	3	?
Vitamin C	4	?
Sorbitol	4	?

[1] Amounts are in kilograms per hectare annually (kg/ha/yr) except where noted by asterisk (L/ha/yr).

[2] Contains nitrogen, phosphorus, and potassium.

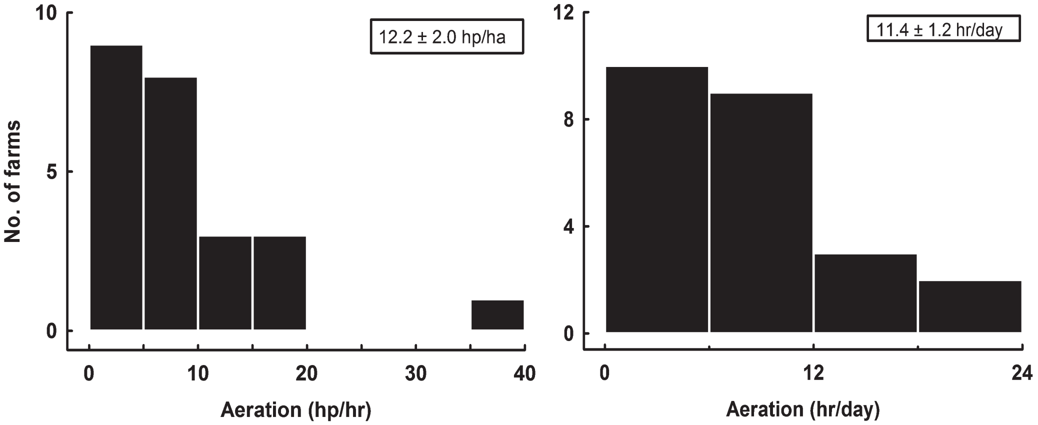

FIGURE 8. *Amounts and hours per day of aeration at* Penaeus monodon *farms in Vietnam. Averages and SEs are in boxes.*

ponds before stocking as a means of destroying wildfish.

Stocking density was usually less than 20 postlarvae/m^2, but six farms stocked between 20 and 40 postlarvae/m^2 and one farm stocked 100 postlarvae/m^2. Crop duration was between 80 and 200 d at 20 farms, but four farms had crops of over 300 d.

Mechanical aerators of the same type used in *L. vannamei* ponds were installed at 16 farms. Aeration capacity ranged from less than 5 hp/ha to nearly 40 hp/ha with an average of 12.2 ± 2.0 hp/ha. Daily duration of aeration usually was ≤12 h with an average duration of 11.4 ± 1.2 h/d (Fig. 8).

Molasses was applied to ponds at only one farm, but all farms used probiotics (Table 6). A total of 10 farms applied zeolite, while one farm applied *Yucca* extract (Table 6). There was little use of mineral mixes or fertilizers. Antibiotic use was reported at three farms, and four farms each used vitamin C and sorbitol.

Production Data. The *P. monodon* farms did not produce large, annual quantities of shrimp – 16 produced less than 2 m.t./yr (Fig. 9). Of the 24 farms, 20 farms applied feed, but some of these applied feed very sparingly. Production, therefore, tended to be low, and 10 farms – including all that did not use feed – had pond production less than 0.5 m.t./ha/yr. Only six farms had pond production intensity between 2 and 6 m.t./ha/yr (Fig. 9). As with *L. vannamei* production, *P. monodon* farms with more crops per year had greater pond production intensity – 1.8 ± 0.4 m.t./ha/yr for one crop per year versus 7.6 ± 1.7 m.t./ha/yr for two or more crops per year. Based on total farm area, production averaged 1.47 ± 0.07 m.t./ha/yr. The survival of shrimp from stocking to harvest varied from less than 10% to nearly 100% with an average of 58.4 ± 6.1% (Fig. 9). The FCR was highly variable with values ranging from 0.8 to 2.0 – the average was 1.71 ± 0.50 m.t. (Fig. 9).

Major Resource Use. The production area expressed as a percentage of total farm area was 55.9% (Table 3); about 0.78 ha additional farm area was devoted to each 1 ha of production area. The total land burden for *P. monodon* production (Fig. 10) ranged from about 0.5 to 15.8 ha/m.t. (average = 2.3 ± 0.1 ha/m.t.). Direct farm water use was variable (10,000–140,000 m^3/m.t.) and averaged 19,000 ± 860 m^3/m.t. Energy use for construction and repair of earthwork was highly variable but averaged 37.4 ± 5.6 GJ/m.t. (Fig. 10). Operational energy ranged from less than 1 GJ/m.t. to about 32 GJ/m.t. (average = 5.4 ± 2.9 GJ/m.t.). Embodied energy in feed averaged 10 GJ/m.t. – slightly greater than operational energy. Farm energy use was 52.6 ± 9.2 GJ/m.t.

Wildfish use for the 20 farms applying feed varied with the FCR and ranged from

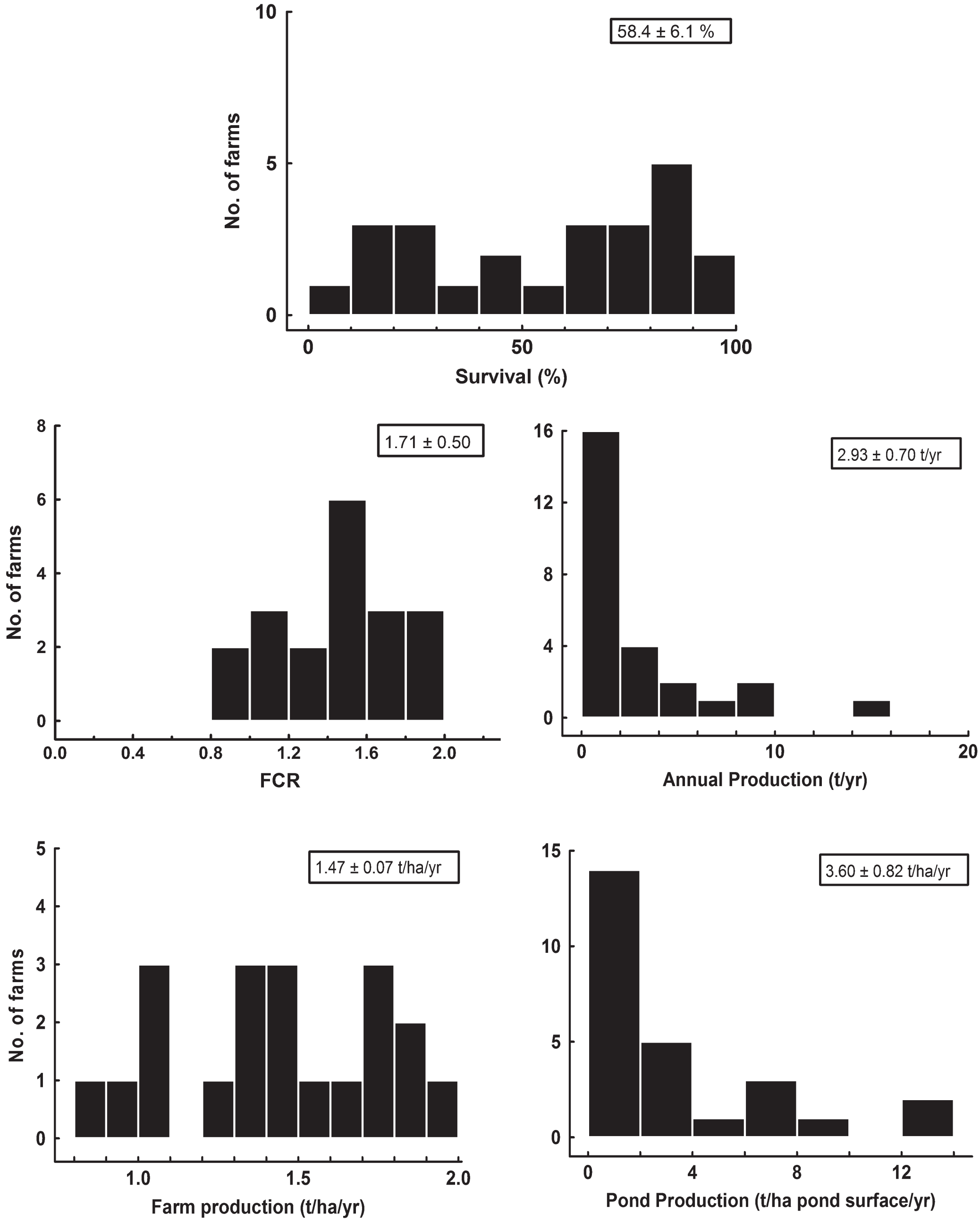

FIGURE 9. *Survival, feed conversion ratio (FCR), total farm production, annual farm production, pond production intensity, and farm production intensity at* Penaeus monodon *farms in Vietnam. Averages and SEs are in boxes.*

about 700 kg/m.t. to 1600 kg/m.t. The average fish-in : fish-out ratio was 1.02 ± 0.10 and similar to that found for *L. vannamei*. The five *P. monodon* farms in Thailand had a fish-in : fish-out ratio below 1.0.

Discussion

The method for selecting farms, though not random, provided a sample of farms in both countries that included several major production

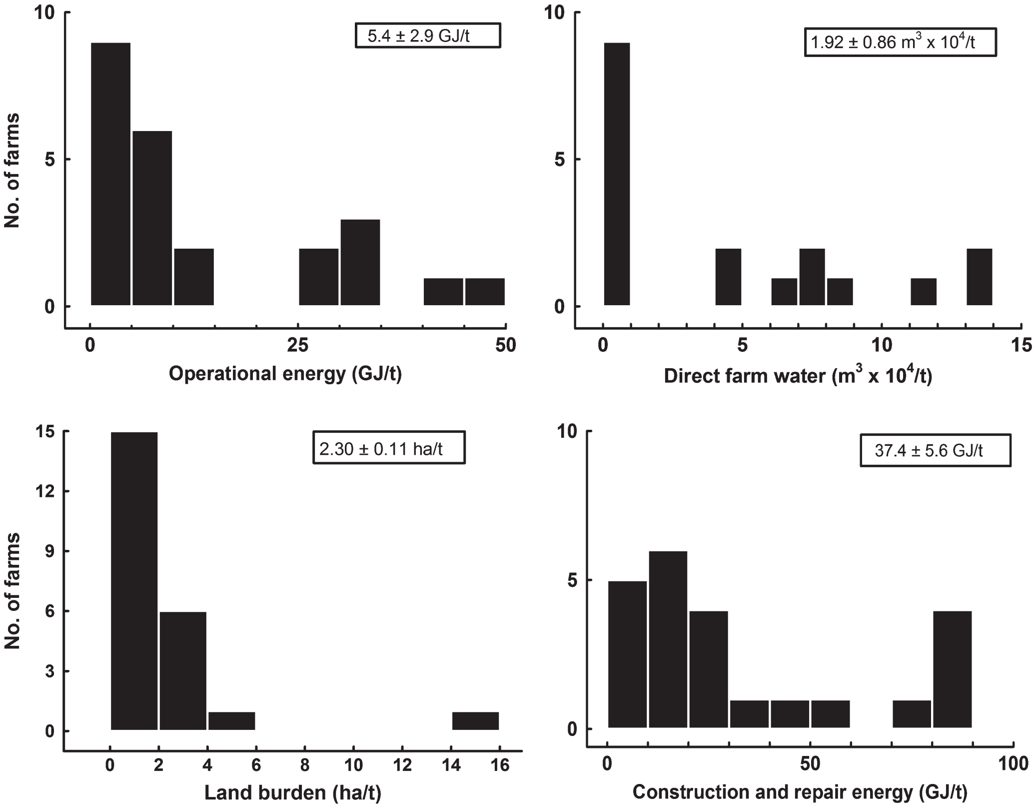

FIGURE 10. *Total land burden for shrimp production, direct farm water use, energy for construction of repair of farm earthwork, and operational energy at* Penaeus monodon *farms in Vietnam. Averages and SEs are in boxes.*

areas and covered a wide range of production intensity. The validity of information provided by farmers was subject to misunderstanding of questions, incomplete records, errors in records, faulty memory of farmers, and, possibly, intentional misrepresentation of facts by farmers. Moreover, despite interviews being conducted in Thai and Vietnamese by native speakers functional in English, there was a possibility of error in translations of interviews to English by the interviewers. One of the authors (CEB) who can speak, read, and write Thai at a functional level sat in on several interviews in Thailand. He believes that the information given by Thai farmers was recorded correctly from records and verbal responses. A similar assessment of the Vietnamese interviews was not possible. In summary, the selection of farms was not truly random and errors no doubt occurred in responses to the interview queries.

With respect to the veracity of different aspects of the data, the areas of farms and earthwork infrastructure – reservoirs, canals, production ponds, and sedimentation basins – were considered most reliable of all the data, because they were taken from maps of farms prepared during construction. The horsepower of aeration in ponds was obtained by counting motors and observing their rated horsepower that was stamped on each motor by the manufacturer. Electricity use at farms was taken from power bills kept by the farmers. Farmers generally had good records of crop duration, feed purchases, and shrimp sales. There was more uncertainty about the amounts of diesel fuel, hours and amounts of aeration used at different times in the production period, and rates at which amendments were applied to ponds. The variable with which we have the least confidence is percentage survival – farmers almost invariably gave this

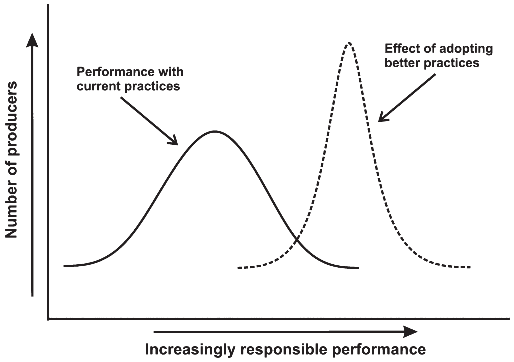

FIGURE 11. *Environmental performance curve and shift to better performance by use of better practices. Source: Modified from Clay (2008).*

statistic from memory, and in many cases, the farmer seemed uncertain.

Wide variation was found in all aspects of shrimp farm infrastructure, operational inputs, and production statistics. A single set of operational procedures was not used across farms – stocking and feeding rates, horsepower of aerators per hectare, duration and amount of aeration, and types and application rates of amendments varied greatly. There was similar variation in production statistics to include stocking density, crop duration, survival, production intensity, and FCR.

As an effort to improve the environmental performance of aquaculture, it has been suggested that a shift by producers with low to average performance to the performance level of producers with better performance through adoption of better practices would move the current performance curve toward better performance as well as narrow the base and increase the peak of the performance curve (Fig. 11). Histograms related to key variables such as survival, FCR, production, farm water use, land use, and operational energy from the survey usually did not exactly follow a normal, bell-shaped distribution as suggested in Figure 11. Nevertheless, the concept illustrated in Figure 11 is valid, because there was a wide range in performance associated with each key variable, and performance at most and possibly all farms could be improved.

Farmers in both countries used many amendments. The large variation in combinations of amendments, differences in management, and other factors would not allow a reliable statistical comparison of production among farms with respect to amendment use. However, several studies have revealed probiotics (bacterial amendments) do not improve water quality in ponds (Tucker and Lloyd 1985; Mischke 2003; Tucker et al. 2009; Li and Boyd 2016) and zeolite does not remove ammonia or other toxic substances effectively (Zhou and Boyd 2014). Liming is beneficial in waters with low pH soil or less than optimal total alkalinity (Boyd and Tucker 1998), but waters of many shrimp ponds are near saturation with calcium carbonate, and, as a result, liming materials do not dissolve (Boyd et al. 2016). The use of burnt lime to disinfect bottom soil in empty ponds often is ineffective because application rates used by farmers are too low to increase pH enough to kill disease organisms and their vectors (Li et al. 2014). Chlorination obviously can be an effective disinfectant if used at a sufficient concentration (White 1992), but the other disinfectants have not been studied as thoroughly as has chlorination. In our opinion, amendments should be used only when there is a reason to expect them to be effective.

Land use information revealed that roughly half of farm areas is devoted to production surface areas. The remainder is occupied by reservoirs, canals, settling basins, embankments, roads, buildings, staging areas, and so on. The land-to-production pond surface area ratios were 2.12 for *L. vannamei* farms in Thailand and 1.97 and 1.79 for *L. vannamei* and *P. monodon* farms, respectively, in Vietnam. This agrees well with a satellite imagery study of a large sample of aquaculture ponds from 26 countries from which an equation was developed for estimating total farm area from average production pond size on farms (Jescovitch et al. 2016). For the average sizes of shrimp ponds in Thailand and Vietnam, the equation predicted land-to-production pond surface ratios of 1.74 for *L. vannamei* farms in Thailand and 1.63 for both *L. vannamei* and *P. monodon* farms in Vietnam. The large *P. monodon* farms in Thailand had much lower land-to-water surface ratios of about 1.20 – also in agreement with prediction by the equation.

The amount of land devoted to shrimp production includes the production water surface area, the farm area supporting the production area, and land necessary to provide plant-based feed ingredients. Average data from *L. vannamei* production in Thailand can be used to illustrate how total land burden for shrimp production would ideally relate to intensity of production in growout ponds. The average farm area : production water surface area was 2.12 (Table 3) – each hectare of production area was supported by an additional 1.12 ha of land on the farm. Feed had an embodied land area of 0.249 ha/m.t. (Table 3), and FCR averaged 1.49, which agrees with larger survey efforts in Vietnam and Thailand conducted by Henriksson et al. (2014). Each ton of shrimp required 0.37 ha of land for feed (0.249 ha/m.t. feed × 1.49). Average pond production intensity in Thailand was 17.31 m.t./ha/yr, and associated land use was 1.0 ha for pond surface, 1.12 ha for support area, and 6.42 ha for feed (0.371 ha land/m.t. feed × 17.31 m.t./ha/yr of shrimp) – a total land burden of 8.54 ha or 0.49 ha/m.t. of shrimp. This calculation was repeated for a range of pond production intensity, and the expected effect of intensification on total land burden is illustrated in Figure 12. Land burden per metric ton of shrimp declines rapidly until production intensity reaches 5 m.t./ha/yr, but it decreases at an increasingly more gradual rate at higher production intensity.

The actual total land burden for *L. vannamei* production (Thailand and Vietnam data combined) exhibited a similar trend of decrease (Fig. 13) as illustrated with the generalized assessment based on average data (Fig. 12) regardless of high variation in FCR among farms. For *P. monodon* production in Vietnam, there was also a marked decrease in total land use that fell quickly as farm production intensity increased to about 5 m.t./ha/yr after which land use declined more slowly with increasing intensity (Fig. 13).

Total water use followed roughly the same pattern described earlier for total land use. Total water use for *L. vannamei* dropped drastically from about 100,000 m^3/m.t. shrimp at a farm production intensity less than 1 m.t./ha/yr to about 200–400 m^3/m.t. at farm production intensities above 5 m.t./ha/yr (Fig. 14). Water use tended to be greater for *P. monodon* than for *L. vannamei*, but the trend in use decreased with greater farm production as it did with *L. vannamei*.

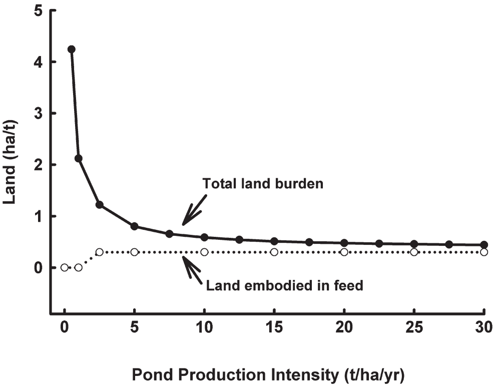

FIGURE 12. *Generalized depiction of effect of pond production intensity on land embodied in feed and total land burden per 1 m.t. shrimp at a feed conversion ratio of 1.49 in Thailand.*

There was much more variation in total energy use among farms than was found for land and water use. This resulted because of large differences among farms in construction and repair energy, pumping energy, and aeration energy. Nevertheless, the trend in total energy use (Fig. 15) for both species – as with land and water – was greater efficiency at greater farm production intensity.

Wildfish use was not correlated with farm production intensity (Fig. 16). Of course, wildfish use is directly related to FCR, because unlike land, water, and energy, there was a single reason for wildfish use – fishmeal in feed.

Intensification appears to lessen the use of land, water, and energy. This may not seem reasonable to many environmentalists and aquaculturists who support small-scale, low-input aquaculture. The reason that intensification saves resources is that much land and water are used for producing each metric ton of shrimp or other aquaculture product when pond production intensity is low. For *L. vannamei*, about 2 ha of land and 100,000 m^3 of water are needed to produce 1 m.t. of shrimp by extensive

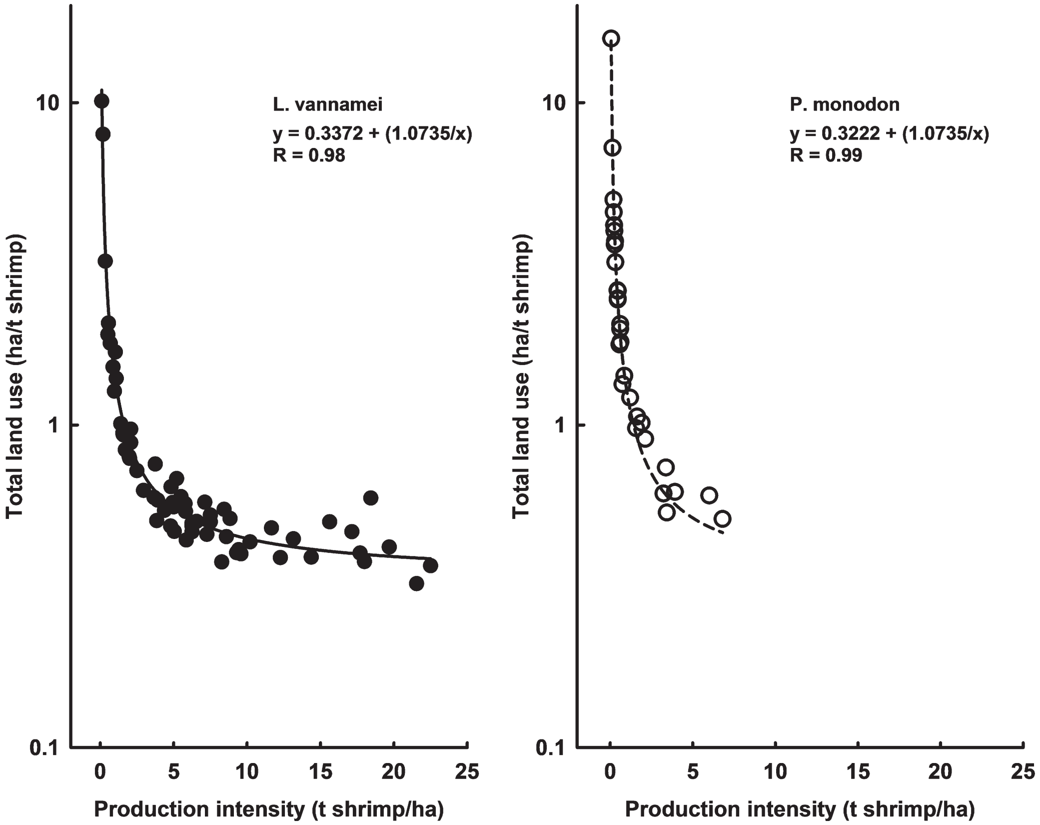

FIGURE 13. *Total land burden versus farm production intensity for* Litopenaeus vannamei *production in Thailand and Vietnam (left) and* Penaeus monodon *production in Vietnam (right).*

culture, while at a pond production intensity of 30 m.t./ha/yr, only 0.444 ha of land and 200 m^3 of water – including land and water embodied in feed – are needed to produce 1 m.t. of shrimp. Putting this on a large scale, suppose in the future *L. vannamei* production in Thailand and Vietnam combined increases 500,000 m.t. to meet future demand. Achieving this increase by extensive culture would require 1,000,000 ha of land for new farms. However, the production increase could be achieved with no additional shrimp farm area by intensification. But, about 250,000 ha (at FCR = 1.5) of additional cropland would be necessary for feed ingredients. Considering that land for shrimp ponds in coastal areas typically is of higher biodiversity than agricultural land (Boyd and McNevin 2016a, 2016b), it appears prudent to save 1,000,000 ha of coastal habitat at the expense of increasing agricultural land by about 250,000 ha.

The argument for intensification to conserve water does not actually apply in shrimp culture, because shrimp farms use brackish water. Nevertheless, reducing water use per metric ton of shrimp lessens the energy use for pumping as well as the amount of farm effluent. Of course, freshwater pond aquaculture is conducted in much the same manner as shrimp culture, and intensification of freshwater aquaculture conserves freshwater (Tucker et al. 2015).

Operational energy use for low-input aquaculture obviously is small, but construction of ponds and other earthen infrastructure requires the same amount of energy irrespective of production intensity. Energy use for construction and repair – even when amortized over time – is higher for extensive aquaculture than for intensive aquaculture. This point is illustrated well in Figure 15; total energy use for low-intensity shrimp culture was around

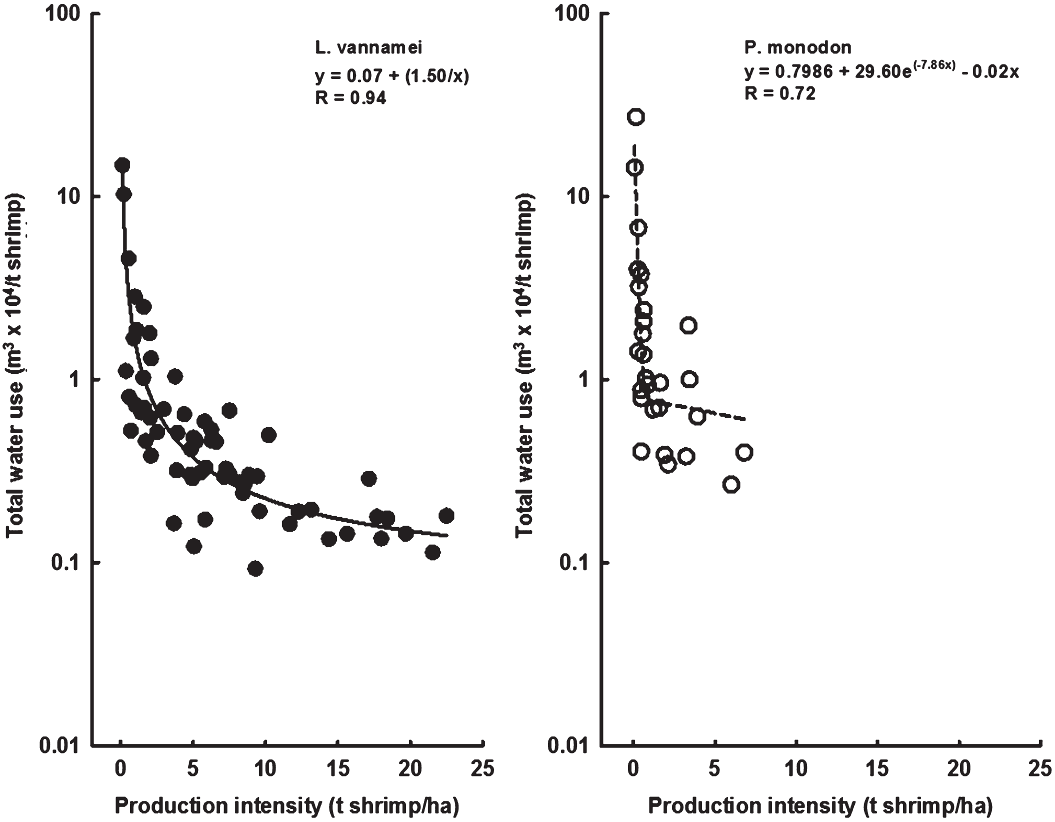

FIGURE 14. *Total water use versus farm production intensity for* Litopenaeus vannamei *production in Thailand and Vietnam (left) and* Penaeus monodon *production in Vietnam (right).*

100 GJ/m.t., but about half of this at a farm production intensity above 5 m.t./ha/yr.

The FCR is of paramount importance in conserving embodied resources in feed and lessening pollution potential. In the case of *L. vannamei* and *P. monodon* feed used in calculations for this study (Table 2), reducing FCR by 0.1 unit (e.g., from 1.4 to 1.3) would provide the following benefits to embodied resource use:

Resource	*L. vannamei*	*P. monodon*
Feed (kg/m.t.)	100	100
Land (ha/m.t.)	0.025	0.023
Freshwater (m^3/m.t.)	112	113
Energy (GJ/m.t.)	0.801	0.968

Expanding these numbers to global feed-based shrimp production of about 2,817,962 m.t. of *L. vannamei* and 563,815 m.t. of *P. monodon* would result in the following reductions in resource use:

Resource	*L. vannamei*	*P. monodon*
Feed (m.t.)	282,000	56,400
Land (ha)	70,450	13,000
Freshwater (m^3)	315,612,000	63,711,000
Energy (GJ)	2,258,000	546,000

Feed for *L. vannamei* and *P. monodon* cost around $1000/m.t. and $1100/m.t., respectively. The savings in feed by reducing the FCR by 0.1 unit would be about $100 and $110 per metric ton of shrimp, respectively. Thus, it is surprising that nearly all producers do not give great emphasis to lessening FCR considering the survey revealed marked variation in FCR among farms. Obviously, some producers are

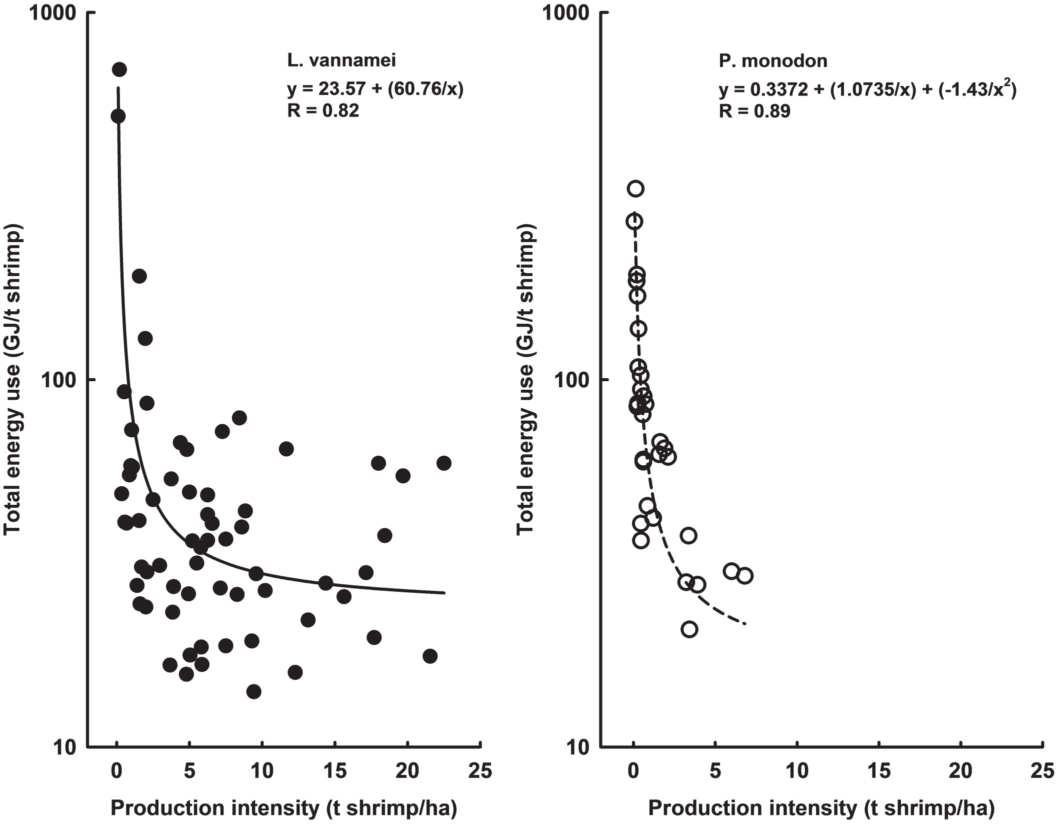

FIGURE 15. *Total energy use versus farm production intensity for* Litopenaeus vannamei *production in Thailand and Vietnam (left) and* Penaeus monodon *production in Vietnam (right).*

using much better feeding practices and maintaining less stressful conditions in ponds through adequate aeration than are other producers.

In addition to lowering feeding costs and conserving embodied resources, diminishing the FCR lessens the waste load per unit of production and diminishes the oxygen demand and potential for acidification and eutrophication of feed-based aquaculture. To illustrate, lowering the FCR by 0.1 unit diminishes the amount of feed necessary to produce 1 m.t. of shrimp by 100 kg. A typical feed for *L. vannamei* contains 39.2% carbon, 5.9% nitrogen, and 1.2 kg phosphorus (Chatvijitkul et al. 2016). The oxygen demand of 100 kg of the feed is equal to about 105 kg O_2 (Boyd 2015), the acidification potential is around 42 kg $CaCO_3$ (Boyd 2015), and the 100 kg feed contains 5.9 kg nitrogen and 1.2 kg phosphorus – the key nutrients causing eutrophication. Thus, lowering FCR has large environmental benefits.

Wildfish use can be lessened by improving FCR, because *L. vannamei* feed requires 818 kg wildfish/m.t., while *P. monodon* feed has 1302 kg/m.t. of wildfish embodied in it (Table 2). Wildfish use can be lessened even more effectively by using fishmeal replacements in feed. Research has shown that fishmeal can be replaced by fish offal meal, shrimp head meal, or various other animal byproduct meals (Amaya et al. 2007; Sookying 2010). It also has been possible in research to replace most or all of the fishmeal in shrimp feed with soybean meal, wheat flour, canola meal, or other plant meals (Davis et al. 2008; Sookying and Davis 2011; Sookying et al. 2013). However, these research findings basically have been ignored by feed producers and farmers. An effort is needed to determine

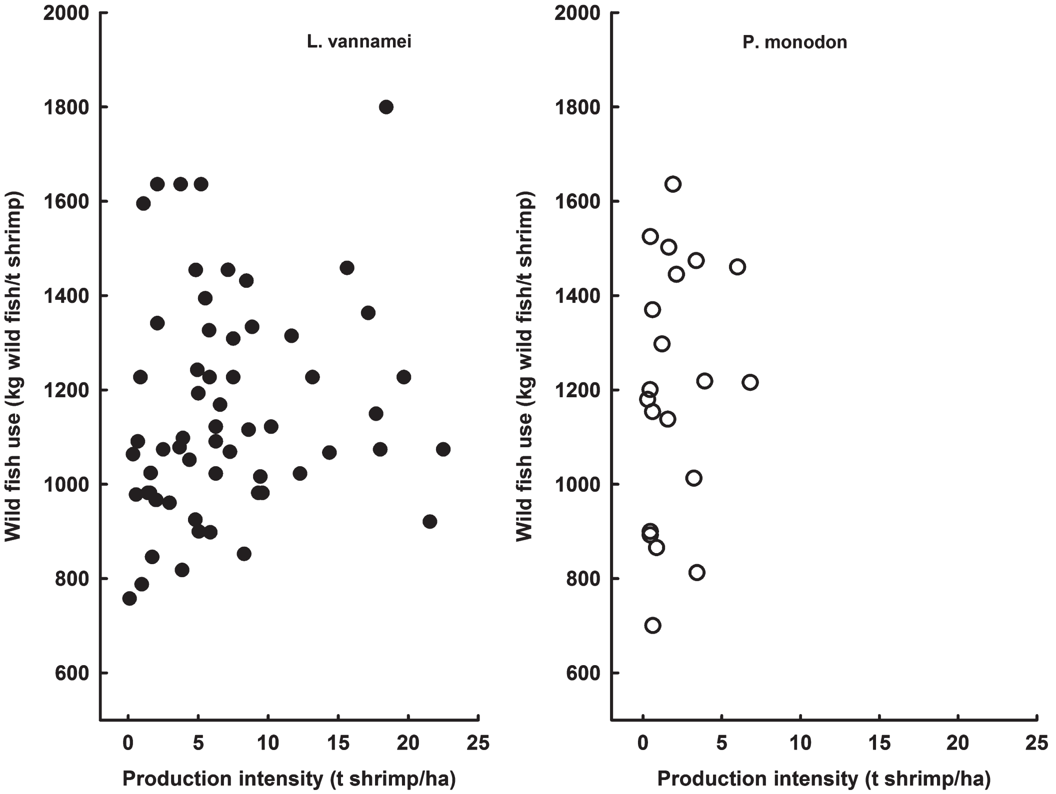

FIGURE 16. *Wildfish use in feed for farm production intensity for* Litopenaeus vannamei *production in Thailand and Vietnam (left) and* Penaeus monodon *production in Vietnam (right).*

whether shrimp feeds containing no fishmeal are equivalent to feeds with fishmeal when used on commercial farms.

Most shrimp certification programs require a fish-in : fish-out ratio of 1.0. However, if shrimp feeds with little or no fishmeal prove as effective as traditional feeds now in use, it seems incumbent upon aquaculture certification programs to require feeds with no fishmeal or at least require a much lower fish-in : fish-out ratio.

Two other indicators – the diel fluctuation of dissolved oxygen concentration in the receiving water body and the percentage survival – were suggested as indicators of efficient and environmentally responsible aquaculture (Boyd et al. 2015). Based on observations made during this survey, these two indicators probably would not be useful in resource use and environmental assessments of most farms. Some shrimp farms included in the present survey seldom discharged water to the outside other than at harvests; but those that did discharged into small canals that led to a receiving body of water often several kilometers from farms. The farm discharge canal was empty or filled with water from other sources unless the farm was actively discharging – often only at harvest. As was found during the survey, visits to farms to collect data seldom would correspond to harvests, and there would be great difficulty in finding a location for measuring diel dissolved oxygen fluctuation. Of course, dissolved oxygen fluctuation in the receiving water could be a useful indicator where a farm discharges directly into a natural water body (e.g., cage culture in lake or reservoir or large, land-based farms that discharge into a lake, river, or estuary).

Use of survival as an indicator in shrimp culture also would be problematic. Postlarvae are tiny and cannot be counted with a high degree of accuracy. Hatcheries typically provide extra postlarvae – usually 10–20% – in counted batches sold to farms to compensate for errors in counting or weak postlarvae liable to die during acclimation or soon after stocking. Farmers in Asia acclimate postlarvae before stocking them in ponds, but they usually do not recount the postlarvae before stocking. Stocking density usually will be higher than the reported density if the postlarvae survive well or lower in case of poor survival. Once placed in ponds, it is not possible to accurately estimate the number of postlarvae that have survived. Although the producer is able to accurately estimate the number of shrimp harvested by determining the average individual weight of shrimp in samples and using this estimate to determine the total number of shrimp harvested from the total weight of shrimp taken from a pond, accurate estimates of survival are impeded by the lack of reliable information on numbers of postlarvae stocked.

Considerable energy was used for mechanical aeration, and the amount of aeration varied greatly among farms and between the two countries. An effort should be made to determine the optimal amount of aeration needed to avoid dissolved oxygen concentration below 3 mg/L at night (Boyd and Tucker 2014). Based on relatively efficient aerators used in the USA, Boyd and Tucker (2014) estimated that 1 hp of aeration should be applied for each 10 kg/ha/d-increment of feed input. In a pond with 15 m.t./ha of shrimp, the feed input would be around 225–250 kg/ha/d, and an aeration rate of 22.5–25.0 kg/ha would be necessary. The floating electric paddlewheel aerators used in Thailand and Vietnam are much less efficient than those used in the USA (Boyd 1998), but the efficiency of the long-arm paddlewheel aerators is not known. It is the opinion of one of the authors (CEB) that these aerators are even less effective than the floating electric paddlewheel aerators.

Improvement in aerator design and studies to determine the optimal amount of aeration (both power and hours of operation per day) at different times during the crop period could greatly decrease energy input for aeration and lessen production costs. Diesel-powered aerators are still used by some shrimp farmers in Asia, but with respect to this study, only at a few of the low-production farms in Vietnam. To achieve 1 hp · h work input to a device such as an aerator shaft usually requires 1 kWh of electricity or 0.335 L of diesel fuel (https://www.extension.purdue.edu/extmedia/AE/AE-111.html). As a result, electricity, if available, usually is more economical than diesel fuel as an energy source. For example, in Thailand, the current price of electricity is $0.0944/kWh (http://www.egat.co.th/en/), while that of diesel fuel is $0.82 L (http://www.globalpetrolprices.com/Thailand/diesel_prices/), making diesel-powered aeration about three times more expensive than electrical aeration. Moreover, 0.335 L of diesel fuel contains 12.2 MJ energy, while a 1 kWh of electricity is equal to 3.6 MJ. Considerable energy savings can result from switching from diesel to electricity-powered aerators.

In parts of Thailand, it is common to use liquid propane gas (LPG) as fuel – especially in automobiles and trucks. None of the farms in the survey used LPG. The energy and water use for capturing wildfish and processing them into fishmeal for inclusion in feed was contained in the embodied resource estimate for shrimp feed (Chatvijitkul et al. 2016). The embodied energy and water in fertilizers (which were seldom used), burnt lime, and agricultural limestone were not considered. The emphasis was on major resource uses and impacts, and energy use was limited to construction and repair of reservoirs, ponds, and other earthwork, pumping water, mechanical aeration, and embodied energy in feed.

Resource use efficiency seems to be a useful indicator of environmentally responsible shrimp culture, and it also could be useful in other kinds of aquaculture. The survey instrument used in this study contained many queries, because we wanted to assure that all necessary information would be obtained. It appears that for practical assessments of resource use such as those made by auditors for aquaculture certification programs, data collection could be limited to a few key items as follows: total farm area devoted to aquaculture; water surface area for production; amount of feed purchased annually; total annual production, amount of electricity, and other fuels used annually; and amount of water pumped into farm. Survival could be included provided farmers would be willing to keep records on the total amount of postlarvae (or fingerlings) purchased annually and provide the average individual weight of animals at harvest.

We believe that surveys that include detailed production data such as Jahan et al. (2015), Henriksson et al. (2014), and the present one should be conducted in other countries that rear shrimp and extended to other species. This information would be valuable in determining the range in resource use across farms for different species and for establishing reasonable limits in certification programs and other improvement efforts for resource use per metric ton or production. Periodic surveys could be used to determine if aquaculture facilities in an area – certified, noncertified, or both – are improving resource use efficiency over time. Without such information, aquaculture will continue to be highly scrutinized by environmental activists and heralded by the industry without factual evidence.

Conclusions

The main findings of this study were as follows:

- Farming practices and resource use differed greatly by farm and no universal resource use and consequential environmental impact assessment can be made at a country or even provincial level.
- Farms for *L. vannamei* and *P. monodon* culture in Thailand and Vietnam varied both with respect to areas and depths of reservoirs, canals, ponds, settling basins, and staging activities and to operational procedures such as stocking density, feed management, water use, aeration, and amendment use.
- The efficiency of land, water, and wildfish use (for fishmeal in feed) for *L. vannamei* was similar between countries despite production tending to be greater in Thailand. However, energy use was greater in Thailand than in Vietnam.
- Culture of *P. monodon* in Thailand was highly extensive and had low inputs. However, the land burden for culture of this species in Thailand is great.
- In Vietnam, *P. monodon* culture was less intensive than *L. vannamei* production, but other than for greater energy use, it was similar in resource use efficiency to *L. vannamei* culture.
- The use of land, water, and energy decreases with increasing farm production intensity for *L. vannamei* in both countries and for *P. monodon* in Vietnam.
- Use of land, water, energy, wildfish, and FCR appear to be useful indicators of efficient, environmentally responsible shrimp culture.
- Percentage survival will indicate farming success, resource use efficiency of feed, and health management, but at least in shrimp culture, this indicator is challenging to obtain because of the inability to accurately account for the number of postlarvae stocked.
- Although diel fluctuation of oxygen in receiving water bodies is indicative of nutrient pollution, access to and location of receiving water bodies is often difficult because many farms must be discharging water to identify the ultimate drainage location into natural water bodies.
- The two most useful farm-level approaches to making shrimp aquaculture – and presumably other types of aquaculture – more resource use efficient and less environmentally degrading are to intensify production and use good feed and water quality management to minimize FCR.
- Wildfish use for feed resulted in a fish-in : fish-out ratio above 1.0 at most farms. Lessening FCR also reduces the fish-in : fish-out ratio. But, the greatest benefit could be achieved by replacing most or all of the fishmeal in shrimp feed with animal byproduct or plant meals – research suggests that this improvement is possible.
- Mechanical aeration is essential for intensification, but improvements in aeration equipment and use are needed badly.

- Many of the amendments used in Vietnamese and Thai shrimp culture appear ineffective, but their use requires embodied resources as well as additional production cost.

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