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Economics of Sustainable Intensification of Aquaculture: Evidence from Shrimp Farms in Vietnam and Thailand

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Abstract

There is growing interest in sustainable intensification of aquaculture production. Yet little economic analysis has been done on farm-level effects of the economic sustainability of production intensification. Data from 83 shrimp farms (43 in Vietnam and 40 in Thailand) were used to identify (through principal component and cluster analyses) 13 clusters of management practices that reflected various scales of production intensity that ranged from 0–1999 kg/ha/crop to 10,000 kg/ha/crop and above, for both *Penaeus monodon* and *Litopenaeus vannamei* in Vietnam and Thailand. The clusters identified reflected sets of management practices that resulted in differing yields despite similarities in stocking densities among some clusters. The enterprise budget analysis developed showed that the more intensively managed clusters outperformed the less intensively managed clusters in economic terms. More intensively managed farm clusters had lower costs per metric ton of shrimp produced and were more profitable. The greater yields of shrimp produced per hectare of land and water resources in more intensively managed shrimp farms spread annual fixed costs across a greater volume of shrimp produced and reduced the cost per metric ton of shrimp. Costs per metric ton of shrimp produced decreased from the lowest to the highest intensity level (from US$10,245 at lowest intensity to US$3484 at highest for *P. monodon* and from US$24,301 to US$5387 for *L. vannamei* in Vietnam and from US$8184 at the lowest intensity level to US$3817 at the highest intensity level per metric ton for *L. vannamei* in Thailand). Costs of pond amendments used in shrimp production were particularly high in Vietnam and largely unwarranted, whereas fixed costs associated with the value of land, production facilities, equipment, and labor were sufficiently high in Thailand so that net returns were negative in the long run. Nevertheless, economic losses in Thailand were less at greater levels of intensification. The study demonstrated a clear value proposition for shrimp farmers to use natural resources (such as land) and other inputs in an efficient manner and supports findings from corresponding research on farm-level natural resource use efficiency. Additional research that incorporates economic analysis into on-farm studies of sustainable intensification of aquaculture is needed to provide ongoing guidance related to sustainable management practices for aquaculture.

KEYWORDS

shrimp economics, sustainability, sustainable intensification, Thailand, Vietnam

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Growth of aquaculture is necessary to provide food for increasing global population levels, and the need for such growth to be developed in a sustainable and responsible manner is widely recognized as a necessary goal. However, much of the literature on sustainability lacks a systematic and data-driven approach from which to identify more sustainable production systems or species (Engle and D'Abramo 2016). To add to the complexity of the search for more sustainable aquaculture production is the reality that businesses must be profitable to be sustained over time. Yet there are few studies that have assessed the economic sustainability of alternatives suggested to increase environmental sustainability.

Studies of aquaculture sustainability have tended to intertwine farm size and intensity of production. "Small-scale" production is often assumed to refer to low-input, extensive, or subsistence production, while "large-scale" is frequently used to refer to intensive production for export markets (Nakamura 1985; Bush et al. 2010). Vandergeest et al. (1999), however, argued that small shrimp farms can be managed as intensively as large farms. This is largely supported by the technical efficiency literature on aquaculture in which farm size has not been shown to consistently explain economic efficiencies of aquaculture production generally (Iliyasu et al. 2014), across counties/provinces within a given country (Tan et al. 2011), or across countries and levels of production intensity within those countries (Dey et al. 2005).

Production intensification, on the other hand, spreads annual fixed costs over greater production volumes (economies of scale) and thereby reduces costs per metric ton of production, for equivalent production systems managed according to profit-maximizing conditions (Engle 2010). The trend toward increasing intensification of shrimp culture is likely driven by economies of scale that are common and widely recognized by aquaculture business managers. However, diseconomies of scale can also occur if businesses grow too large to be managed efficiently or through overcapitalization. Some authors (Thongrak 1995; New 1996; Patmasiriwat 1997) have argued that low-input extensive systems are more economically efficient than more intensive production and cite lower feed conversion ratios (FCRs), fewer disease problems, and greater rates of return. For US catfish production, adoption of more intensive production systems has been shown to reduce (Kumar et al. 2016) or increase (Goode et al. 2002) per-unit costs of production depending on the capital requirements, production performance, and relative prices and costs.

There is agreement in the aquaculture sustainability literature on the importance of access and availability of capital (Bush et al. 2010; Belton and Little 2011). While greater capital is needed for more intensively managed farms, even extensive production of aquaculture crops often requires greater capital than does artisanal fishing or rice farming. Intensification increases requirements for both capital and management skill. Even if strong economic incentives exist to improve productivity, farmers without adequate capital or management skill will be unable to benefit from productivity gains (Waite et al. 2014).

Recent calls for sustainable intensification of food production (Little et al. 2012; Waite et al. 2014; FAO 2016) may indicate an increased understanding of the potential environmental–economic–social benefits of intensification of aquaculture production. The Food and Agriculture Organization of the United Nations (FAO) highlighted examples of 12 sustainable intensification aquaculture systems, one of which was closed/semi-closed intensive production of shrimp in Thailand. However, no economic analysis was performed of the shrimp systems highlighted.

There is a surprising lack of farm-level economic analysis related to effects of intensification levels in aquaculture. Moreover, while there has been a tendency to define intensification based on stocking density (World Bank and MOFI 2006; Joffre and Bosma 2009), Johnson et al. (2014) showed that the combined set of management practices, rather than a single production parameter such as stocking density, must be considered when assessing farm-level economic performance. Detailed farm-level data and analyses are needed to determine the effects of intensification on farm economic performance in major shrimp-producing countries.

Using farm-level survey data from Thailand and Vietnam, Boyd et al. (2017) showed that intensive shrimp production is more efficient, uses fewer resources, and results in less environmental impact per metric ton of shrimp produced than more extensive shrimp production systems. The present study used the same farm-level survey data to assess whether more intensive shrimp production was economically preferable to less intensive shrimp production in Thailand and Vietnam. Specific objectives were to (1) compare cost structures and total costs across production intensity levels, (2) compare net returns above variable costs (short-term profits), and (3) compare net returns above total costs (long-term profitability) across production intensity levels in Thailand and Vietnam. Results of this analysis contribute to the ongoing search for ways to improve sustainability of the resources used in shrimp production in a way that is also economically sustainable.

Methods

A survey was conducted in 83 farms (43 in Vietnam and 40 in Thailand) from April to November 2015. The survey covered a purposive sample of farms in each country and included farms that raised shrimp in a variety of levels of intensity in three provinces in Vietnam and seven provinces in Thailand. The survey instrument elicited information on the farm size, equipment used, production practices (stocking density, feeding rates, aeration rates, length of production cycle, number of crops used, and average size of shrimp harvested), and production input quantities and costs. Farmers were asked to report data for the previous production year. Response rates for the survey were 100% in Vietnam and 98% in Thailand.

Surveys of commercial aquaculture farms demonstrate substantial variation in management decisions related not just to stocking density but also to feeding rates, aeration rates, and harvesting strategies. Recent examples of such variability and the interrelated effects on farm yields and per-unit costs of production can be found in Johnson et al. (2014) and Kumar and Engle (2017). Such variation is not unique to aquaculture, and multivariate techniques have been developed to group observations in a way that identifies sets of on-farm management strategies that are not only distinct from each other but also minimize within-group variation (MacQueen 1967). Cluster analysis is a useful multivariate tool that does not require prior information on the population (Pielou 1984) but yet identifies groups of homogeneous entities that are distinct from other groups (Prein et al. 1993; Hair 1995; Johnson and Wichern 2007).

The approach used in this study to identify groupings of farms with similar management strategies followed that of Johnson et al. (2014) and Kumar and Engle (2017). A principal component analysis was conducted to identify sets of variables that contributed similarly to the overall variability within the data set.

The second stage of the analysis was to group the observations into clusters with similar characteristics. A cluster analysis (agglomerative hierarchical algorithm) was conducted to identify groups of farm observations that were more similar to each other than to observations in the other clusters in terms of key variables such as country, species raised, pond size, stocking density, feeding rate, aeration use, and number of days in production of each crop.

Complete enterprise budgets were developed for each cluster identified based on standard budgeting techniques (Engle 2010). Copies of complete budgets are available on request from the corresponding author. ANOVA was performed on key parameters that included stocking rate, survival, yield, feeding rate, FCR, days per crop, number of crops per year, pond size, and farm size. Mean values that were not significantly different from those of other clusters were averaged across all clusters for use in enterprise budgets. When significant differences were found, mean values for each cluster were used in the corresponding budget. Survival rates used were the averages as reported by farms.

Tables of investment and depreciation costs of land, ponds, reservoirs, buildings, other infrastructure items, and equipment were first developed for the relevant farm size and then converted to a per-hectare basis. Tables of annual costs and returns were based on the mean pond size for each cluster. Values for all line items were converted to a per-hectare basis and multiplied by the mean pond size (in hectares) for each budget for each cluster.

Results

Principal Component and Cluster Analyses

Eight principal components were found to account for 98% of the variability in the data set (Table 1). Specific variables included in these eight principal components were country, species raised, amount of aeration, pond size, and the number of days in production of each crop. Thirteen clusters were identified that minimized the production and management variability within each, including eight clusters in Vietnam and five in Thailand (Table 2). Clusters identified included production of *Litopenaeus vannamei* at all intensity levels in both countries, production of *Penaeus monodon* at all intensity levels in Vietnam, and *P. monodon* production at a very extensive level in Thailand. The most extensive level of production in Thailand was a system that relied on water exchange from tidal flows that introduced blood cockles and mangrove crabs, which were then harvested and sold in addition to shrimp from the ponds, and was also distinct from the least intensive production system of *P. monodon* in Vietnam. The clusters identified resulted in four categories of production intensity as identified by differences in yields of shrimp as follows: very high (yields of 10,000 kg/ha/crop and above), high (yields of 5000–9999 kg/ha/crop), medium (2000–4999 kg/ha/crop), and low (0–1999 kg/ha/crop). Tables 3 and 4 present the mean values of key production variables for each cluster that included stocking density, feeding rate, aeration rate, and yield, among others.

Mean farm size was significantly different ($P < 0.05$) between countries (mean farm size of 2.2 ha in Vietnam and 7.7 ha in Thailand). Mean pond size (3620 m^2) did not differ significantly across clusters within Vietnam but did differ by cluster in Thailand. In Thailand, the very high, high, and medium clusters had a mean pond size of 6737 m^2, whereas the low-yield cluster with *L. vannamei* had a mean pond size of 4000 m^2. With *P. monodon* in extensive production in Thailand, the mean pond size was 9.9 ha.

TABLE 1. *Principal components and eigenvalues.*

Principal component	Eigenvalue	Percent variance (%)	Cumulative variance (%)
1	3.084	34	34
2	2.171	24	58
3	1.312	15	73
4	0.656	7	80
5	0.553	6	86
6	0.509	6	92
7	0.391	4	96
8	0.207	2	98

TABLE 2. *Clusters identified for economic analysis, survey of shrimp farms in Vietnam and Thailand, 2015.*

Country	Species	Intensity category	Yield range (kg/ha/crop)
Vietnam	*Penaeus monodon*	Low	0–1999
Vietnam	*P. monodon*	Medium	2000–4999
Vietnam	*P. monodon*	High	5000–9999
Vietnam	*P. monodon*	Very high	10,000 and above
Vietnam	*Litopenaeus vannamei*	Low	0–1999
Vietnam	*L. vannamei*	Medium	2000–4999
Vietnam	*L. vannamei*	High	5000–9999
Vietnam	*L. vannamei*	Very high	10,000 and above
Thailand	*P. monodon*	Low	0–1999
Thailand	*L. vannamei*	Low	0–1999
Thailand	*L. vannamei*	Medium	2000–4999
Thailand	*L. vannamei*	High	5000–9999
Thailand	*L. vannamei*	Very high	10,000 and above

Production Performance across Levels of Intensification

Yield and feeding rate increased as the intensity of shrimp production increased, regardless of country or species raised (Tables 3 and 4). There were some differences between countries for the very high intensity level, with mean yields in Thailand (13,560 kg/ha/crop) greater than those at the same intensity level in Vietnam (11,324 kg/ha/crop for *P. monodon* and 11,702

TABLE 3. *Mean values for key production parameters by categories of intensity/yield levels, Vietnam clusters.*

	Penaeus monodon				*Litopenaeus vannamei*			
Item	Low	Medium	High	Very high	Low	Medium	High	Very high
Stocking density (PL/m^2)	12	23	58	59	26	31	66	73
Feeding rate (kg/ha/crop)	1119	5822	11,318	14,116	1246	4556	9114	15,485
Days in crop	143	124	120	90	102	90	87	110
Aeration rate (hp/ha)	8	10	21	21	4	12	28	50
Yield (kg/ha/crop)	895	3790	7962	11,324	265	3469	6974	11,702
Feed conversion ratio	1.25	1.54	1.42	1.25	4.7	1.31	1.31	1.32
Harvest weight (shrimp/kg)	40	37	41	66	58	85	72	59
Survival (%)	49	74	83	70	23	75	81	81
Crops per year	1	1	2	3	2	2	2	2

PL = postlarvae.

TABLE 4. *Mean values for key production parameters, by categories of intensity/yield levels, Thailand clusters.*

	Penaeus monodon	*Litopenaeus vannamei*			
Item	Low	Low	Medium	High	Very high
Stocking density (PL/m^2)	2	62.5	62.5	82	99
Feeding rate (kg/ha/crop)	0	1681	4797	10,956	18,666
Days in crop	Year-round	93	92	92	95
Aeration rate (hp/ha)	0	9	33	35	49
Yield (kg/ha/crop)	196	1301	3483	6982	13,560
Feed conversion ratio	n.a.	1.29	1.38	1.57	1.38
Harvest weight (shrimp/kg)	Not reported	70	66	64	57
Survival (%)	20	75	67	73	80
Crops per year	1	2	2	2	2

n.a. = not applicable (no feed was used by farms in this cluster); PL = postlarvae.

kg/ha/crop for *L. vannamei*). Yields of the other intensity levels in Thailand were more similar to those in Vietnam. In Vietnam, the mean yield values for the two species raised within each intensity level were similar, while in Thailand, the only observations of *P. monodon* production were at a very extensive level, with very low yields. Feeding rate differences showed similar patterns, with the exception that farms in the low-intensity production cluster of *P. monodon* in Thailand used no feed.

Stocking density generally increased with increasing levels of production intensity (Tables 3 and 4). Higher intensity levels of *P. monodon* production in Vietnam were associated with a shorter production cycle, from 90 d/crop at the higher intensity levels to 143 d/crop for the lower intensity levels. However, there was no clear trend in the days required to produce a crop for *L. vannamei* production in either Vietnam or Thailand. The number of crops produced per year showed similar results in that higher intensity of *P. monodon* production in Vietnam was associated with a greater number of crops raised in a year, whereas most of the clusters associated with production of *L. vannamei* in both Vietnam and Thailand produced two crops a year. Farms in the most extensive management clusters reported significantly lower survival rates (20–40%) as compared with farms in the medium to very high intensity clusters (68–83%).

Economic Performance across Levels of Intensification

Gross receipts per hectare per year increased with greater production intensity, across all clusters, as would be expected (Tables 5 and 6). The greater yields produced at greater levels of intensity resulted in greater volumes of shrimp sold that resulted in greater gross receipts.

TABLE 5. *Key economic results of enterprise budget analyses, Vietnam clusters.*[a]

Item	*Penaeus monodon*				*Litopenaeus vannamei*			
	Low	Medium	High	Very high	Low	Medium	High	Very high
Gross receipts	$5601	$23,718	$99,654	$191,340	$3435	$44,969	$90,405	$151,695
Feed cost	$1572	$8181	$31,809	$59,510	$3502	$12,805	$25,615	43,521
PL cost	$467	$894	$4511	$6883	$2162	$2577	$5487	$6069
Amendment cost	$992	$2261	$5248	$5248	$986	$4106	$21,556	$48,033
Sediment removal cost	$334	$419	$1110	$2628	$283	$583	$665	$718
Energy (total electricity and fuel)	$339	$2667	$3422	$3422	$526	$924	$2182	$2336
Labor	0	0	$2964	$24,080	0	0	$5186	$7588
TVC	$4550	$16,412	$55,239	$113,371	$8372	23,905	67,676	$120,102
Income above variable costs	$1051	$7306	$44,415	$77,970	−$4937	$21,065	$22,729	$31,594
TFC	$4619	$4645	$4967	$4981	$4508	$4690	$5100	$5972
Total cost	$9169	$21,057	$60,206	$118,352	$12,879	$28,594	$72,777	$126,073
Net returns	−$3568	$2662	$39,446	$72,988	−$9444	$16,375	$17,629	$25,622
BEP above VC	$5.08	$4.33	$3.47	$3.34	$15.80	$3.45	$4.85	$5.13
BEP above TC	$10.24	$5.56	$3.78	$3.48	$24.30	$4.12	$5.22	$5.39
BEY above VC	727	2623	4413	6710	646	1844	5221	9265
BEY above TC	1465	3365	4810	7004	994	2206	5614	9725

BEP above VC = breakeven price above variable costs; BEP above TC = breakeven price above total costs; BEY above VC = breakeven yield above variable costs; BEY above TC = breakeven yield above total costs; PL = postlarvae; TFC = Total fixed costs; TVC = total variable costs.

[a]Values calculated in US$/ha/yr.

Variable costs, by definition, are costs that increase with greater levels of production. Tables 5 and 6 show that individual variable costs per hectare per year, that is, the cost of postlarvae, feed, energy use (electricity and fuel), amendments, labor, and total variable costs per pond, generally increased with the intensity of production in both countries and for both species produced.

Total fixed costs per hectare per year also increased generally with the level of production intensity for both countries and species. The greater total fixed costs on farms that produce at greater levels result primarily from additional investment in equipment such as aeration systems and various types of vehicles. This additional investment enters into annual costs and returns in the form of annual depreciation and interest on the investment. Annual depreciation accounts for the need to provide an annual accounting for the capital that will be needed to replace equipment when worn out. Charging interest on the investment in the annual costs and returns table standardizes either the interest paid if capital were borrowed to finance the equipment purchase or to account for the opportunity cost of equity capital invested in the farm that would have earned some amount of interest if invested differently.

Costs per metric ton of shrimp produced decreased from the lowest to the highest intensity levels for each species in each country. For *P. monodon* production in Vietnam, the cost per metric ton at the lowest intensity level was US$10,245 and decreased to US$3484 at the highest intensity level. For *L. vannamei* production in Vietnam, costs per metric ton decreased from US$24,301 at the lowest intensity level to US$5387 at the highest intensity level. In Thailand, costs per metric ton for *L. vannamei* decreased from US$8184 at the lowest intensity level to $3817 at the highest intensity level.

Net returns per hectare per year for the Vietnamese clusters showed increasing overall profits with increased levels of production intensity, with the lowest intensity level of *L. vannamei* showing an overall loss (Fig. 1). In Thailand, all farms showed negative net returns above all costs (Fig. 2). However, as the level of intensity of production increased, the magnitude of losses decreased for *L. vannamei* production. Income above variable costs was positive, indicating

TABLE 6. *Key economic results of enterprise budget analyses, Thailand clusters.*[a]

Item	*Penaeus monodon*	*Litopenaeus vannamei*			
	Low[b]	Low[c]	Medium	High	Very high
Gross receipts	$653	$8673	$23,220	$46,547	$90,400
Feed cost	0	$3736	$10,660	$24,347	$41,480
PL cost	$28	$4167	$4167	$5467	$6600
Amendment cost	0	$1389	$992	$1924	$5301
Sediment removal cost	0	0	$345	$476	$659
Energy (total electricity and fuel)	$30	$2315	$5343	$5850	$6384
Labor	0	0	$313	$1639	$7763
TVC	$2258	$13,668	$25,734	$45,839	$83,310
Income above variable costs	−$1605	−$4994	−$2514	$707	$7090
TFC	$1104	$11,895	$17,117	$17,856	$20,198
Total cost	$3362	$25,563	$42,850	$63,694	$103,508
Net returns	−$2709	−$16,889	−$19,630	−$17,149	−$13,108
BEP above VC	$11.52	$5.25	$3.69	$3.28	$3.08
BEP above TC	$17.15	$9.83	$6.14	$4.56	$3.81
BEY above VC	677	2050	5201	6876	12,496
BEY above TC	1009	3834	8660	9554	15,526

BEP above VC = breakeven price above variable costs; BEP above TC = breakeven price above total costs; BEY above VC = breakeven yield above variable costs; BEY above TC = breakeven yield above total costs; PL = postlarvae; TFC = Total fixed costs; TVC = total variable costs.

[a]Values are US$/ha/yr.

[b]The very extensive *P. monodon* cluster had an average pond size of 9.9 ha, much larger than all other clusters.

[c]The low intensity of *L. vannamei* cluster had significantly smaller ponds, 0.4 ha as compared with 0.67 ha ponds in the other *L. vannamei* clusters.

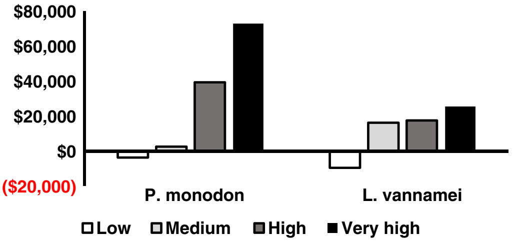

FIGURE 1. *Net returns (US$/ha/yr), Vietnam.*

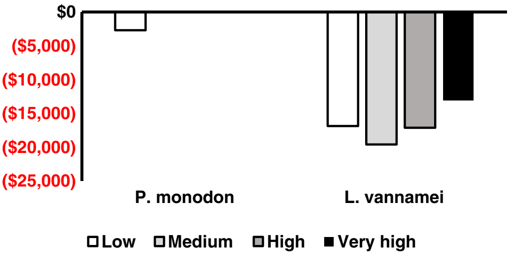

FIGURE 2. *Net returns (US$/ha/yr), Thailand.*

short-run profitability, for the very high and high intensity clusters only.

Within each country and species type, the relative importance of the fixed costs associated with the investment in land, infrastructure, and equipment decreased as the intensity level increased. In Vietnam, the contribution of annual fixed costs to total costs decreased from 50 to 4% as intensity increased for *P. monodon* and from 35 to 5% for *L. vannamei*. In Thailand, the contribution of annual fixed costs to total costs decreased from 46 to 20% as production intensity increased. This decrease in the relative importance of annual fixed costs demonstrates a more efficient use of the fixed resources of land and investment capital with a greater intensity of production. The greater importance of annual fixed costs at the very high yield level in Thailand may explain the lack of long-term profitability demonstrated in the budget analysis in Thailand as compared with Vietnam.

Table 7 lists the various types of amendments reported on the survey questionnaires and included more than 90 different types of lime, minerals, antibiotics, probiotics, vitamins,

TABLE 7. *Amendments used on shrimp farms in Vietnam and Thailand, as reported by respondents.*

Category	Name reported	Vietnam	Thailand
Lime	Calcium carbonate		X
	Calcium chloride		X
	Calcium dioxide		X
	Calcium hydroxide		X
	Calcium oxide	X	X
	Calcium sulfate		X
	Daimetin	X	
	Dolomite	X	X
	Lime	X	X
Water amendments	Biopond	X	
	Biowaste	X	
	Hydrogen peroxide	X	
	Magnesium chloride		X
	Magnesium sulfate		X
	Potassium chloride		X
	K_2NO_4	X	
	pH Buser	X	
	Sodium bicarbonate		X
	Sodium sulfate		X
	Tapondpro	X	
	Zeolite	X	X
Minerals	ADP	X	
	Azomite		X
	CAPHOT	X	
	Himineral	X	
	HP9	X	
	Mineral A	X	
	Mineral CAMID	X	
	Minomix	X	
	Other minerals	X	X
	Pondmin	X	
	Remix	X	
Disinfectants	Aquadine	X	
	Benzalkonium chloride (BKC)	X	X
	Biodin	X	
	Biodine	X	X
	Chlorine	X	X
	Chlorite	X	
	Clear 80	X	
	Dimetyle	X	
	Dine 9000	X	
	Hidine	X	
	Tea seed		X
	Vikon	X	

TABLE 7. *continued*

Category	Name reported	Vietnam	Thailand
Fertilizer	Brown sugar		X
	DAP	X	
	DAB	X	
	Fertilizer	X	X
	Molasses		X
	Phosphorus	X	
	Red sugar		X
	Yuca	X	
Insecticides/ pesticides	Derris grass		X
	Saponin	X	X
	Trichlorfon		X
Disease treatment	Copper sulfate	X	X
	Formaldehyde	X	
	Gluteraldyde	X	
	Metabisulfite	X	
	Potassium permanganate	X	X
Antibiotics	Antibiotics	X	
	Amoxicillin	X	
	Ciprofloxacin	X	
	Enrofloxacin	X	
	Oxytetracycline	X	
Probiotics	Aquamax	X	
	BST	X	
	BZT	X	
	EM	X	
	Navet Biozyme	X	
	Probiotics	X	X
	Super Biotic	X	
	Super Fixer		X
	Super Murras	X	
	Super PH Brand		X
	Super PS	X	
Vitamins	Biosortol	X	
	Vitamin C	X	
	Vitamins	X	
Other	Chitosan	X	
	Metabisulfite	X	
	Other	X	
Unknown	ABS	X	
	BBM	X	
	Hitech	X	
	Nasbaq	X	
	NTS/NT5	X	
	Organic Gold	X	
	Osanet Shell	X	
	Sun Terex	X	
	Super Info	X	
	Truong Hai Hepatic	X	
	TCK	X	

fertilizers, disinfectants, and compounds used for sterilization. Given the substantial effect of the costs of these amendments, particularly in Vietnam, shrimp production costs were estimated with and without the cost of amendments. Depending on the specific cluster, the cost per metric ton of shrimp produced was reduced by \$170/m.t. to \$2262/m.t. in Vietnam and from \$0/m.t. to \$435/m.t. in Thailand by eliminating the use of amendments. While some amendments, such as lime or minerals, are necessary for good survival and growth of shrimp, daily use of antibiotics in shrimp feed, some of which are banned for use in livestock feeds in the USA, EU, Japan, and other countries, or other amendments for which there is little clear evidence of effects on survival and growth, represent opportunities to reduce overall costs of producing shrimp.

Discussion

Farm-level data are inherently variable because no two farmers have the same operating protocol, access to capital, work force, and management skill and experience. Attempts by researchers, policy makers, or environmentalists to categorize a particular race or culture of aquaculture producers are flawed because of this variability. Economic outcomes of an individual farm reflect a set of choices (related to stocking density, aeration rates, and feeding rates) made by managers. Identifying management clusters reduced this variability and allowed for identification of patterns and trends related to the economics across management clusters of different intensity levels. The cluster analysis clearly showed that the overall level of production intensity, as defined by the differing yields that resulted from the total set of management practices, was a key distinguishing factor in terms of which farms were more similar to each other and, thus, to the determination of clusters.

Results of this analysis also point to the need for data obtained from commercial farms rather than strictly from experimental research. An experimental study to assess the effects of intensity of production would likely have established stocking densities that varied based on some arithmetic increment, while holding all other variables (such as feeding, aeration, and harvesting strategies) constant. However, farms are managed based on day-to-day decisions that can be affected by cash flow, incidence of disease, influence from peers, and other reasons that result in categories, in this case of stocking densities, that do not represent orderly increments, but yet resulted in statistically distinct levels of shrimp yields.

This study found that categorizing levels of intensification by initial stocking density may obscure the effects of intensification on cost efficiencies and profitability. The extensive literature on the economics of aquaculture shows that yields often have the greatest effect on per-unit costs of production. Moreover, yields are not solely a function of stocking density, but result from the combined and interrelated effects of stocking density, aeration levels, and feeding rates, among others. Johnson et al. (2014) similarly found that cost per unit of production, and hence profitability, can be quite different even with similar stocking densities. In this study, in Vietnam, the mean stocking density of *P. monodon* in the high-yield cluster ($58/m^2$) was similar to that in the very-high-yield cluster ($59/m^2$). However, the yield in the very-high-yield cluster was 42% greater than in the high-yield cluster, due primarily to a 94% greater feeding rate across three crops per year as opposed to two crops per year in the high-yield cluster. In Thailand, the mean stocking densities were the same ($62.5/m^2$) between the low- and medium-yield clusters for *L. vannamei* production. However, the yield in the medium cluster was 2.7 times greater than that in the low density due primarily to a feeding rate that was 2.9 times greater and an aeration rate that was 3.7 times greater than that of the low-yield cluster. Thus, this study provides evidence from shrimp farms that supports those of Johnson et al. (2014) for catfish farms on the importance of use of multivariate tools such as cluster analysis to identify similar sets of management practices as the basis for comparative economic analyses.

Farm size was not significant in the principal component analysis, supporting the assertion by Vandergeest et al. (1999) that farm size does not necessarily dictate the level of production intensity. For example, farms managed at the very high intensity level were of sizes that ranged from 1 to 18 ha in Vietnam and 2 to 28 ha in Thailand. The more extensively managed farms in Thailand averaged 9.9 ha, larger than the 7-ha average size of more intensively managed farms. Thus, it may be more useful to discuss shrimp production intensity in Thailand and Vietnam as a factor that is separate from farm size.

This study showed that increasing intensification of shrimp production resulted in increased profits in the short run in both countries. Such a finding is generally consistent with economic analyses of aquaculture in that greater yields spread fixed costs over greater amounts of production (Engle 2010). In an earlier study of the profitability of extensive shrimp farming in Vietnam, profitability increased as yields increased with use of higher-quality inputs (Brennan et al. 2000). In a recent study of intensification of catfish production through investment in split-pond systems, Kumar et al. (2016) showed improved profitability as per-unit costs of production were reduced. Revenues from the greater yields exceeded the additional annual fixed costs of the increased investment.

The lack of long-term profitability of shrimp farming in Thailand is, of course, affected by early mortality syndrome (EMS), but also may reflect increasing opportunity costs of land and capital for uses other than shrimp farming. Land values and construction costs for production facilities have increased in recent years and increased fixed costs. Greater fixed costs, combined with losses due to EMS, may partially explain the lack of long-run profitability and, hence, economic sustainability of shrimp farming in Thailand. Additional work is needed to determine conclusively whether the lack of profitability can be attributed to macroeconomic factors that have resulted in increased land and capital costs. An alternative explanation may be that shrimp farming in Thailand has become overcapitalized. For shrimp farming to be sustained in Thailand over the long term, the farms must generate sufficient revenue to be able to replace equipment and production facilities as these wear out. It is not uncommon for well-established industries to "live off depreciation" by not replacing equipment and production facilities in a timely manner and not accounting for the noncash costs of depreciation. Additional, in-depth research is needed to conclusively determine the root causes of the lack of long-run profitability of shrimp farming in Thailand and develop guidance for shrimp farmers.

Although more intensive production of shrimp was shown in this study to be more profitable, the ability of a farmer to shift to more intensive production practices depends on the farm's access to sufficient capital to provide electrical service to the farm and to purchase the aeration equipment, postlarvae, and feed needed. It also depends on the farm manager having sufficient experience, knowledge, and management skill to successfully operate a more intensively managed farm. Access to capital (whether through formal channels such as banks, or informal networks of friends and family), the level of experience and knowledge, and location differences that affect the availability of water control structures in some locales and not others have been shown to restrict a farm's ability to take advantage of more profitable shrimp production systems (Lebel et al. 2010; Marks 2010).

The excessive use of amendments to ponds identified in this study, particularly in Vietnam, has been reported previously by other authors (Gräslund and Bengtsson 2001; Boyd 2002). While some types of amendments, such as lime or minerals, are no doubt necessary given the water quality in particular farms, in other cases, substances such as antibiotics banned for use in many countries and other substances that could not be identified specifically were purchased and used by Vietnamese farmers. There was insufficient detail in the data set to separate the economic effects of various types of amendments used. Moreover, the use of banned antibiotics in aquaculture production and their indiscriminate use for other livestock has the potential to increase bacterial resistance to those antibiotics that are important in human medicine (Rahman et al. 2016). This study showed strong economic incentives to reduce shrimp production costs in Vietnam by restricting pond amendments only to those that have been proven to have expected results.

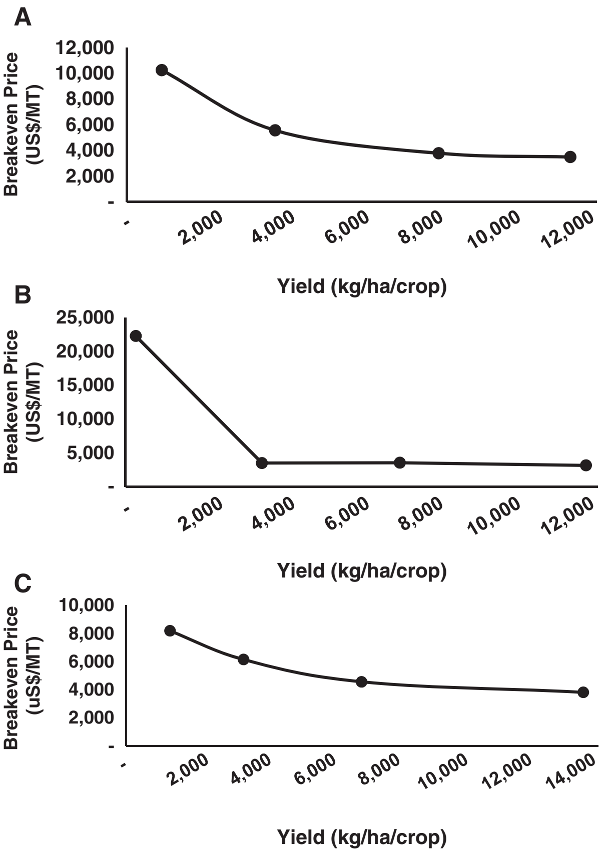

FIGURE 3. *(A) Effect of increased production per hectare on production cost per metric ton,* Penaeus monodon*, Vietnam. (B) Effect of increased production per hectare on production cost per metric ton,* Litopenaeus vannamei*, Vietnam. (C) Effect of increased production per hectare on production cost per metric ton,* L. vannamei*, Thailand.*

Boyd et al. (2017) found that fewer resources were used per metric ton of shrimp produced on more intensive farms. The economic analysis in the present study supported this finding in that production cost per metric ton of shrimp produced decreased as production intensity (and yield) increased (Fig. 3A, B, C). Chatvijitkul et al. (2017) showed that achieving lower FCRs reduced costs as well as environmental impacts associated with fish and shrimp production. Thus, there is a clear value proposition for farmers to become more efficient in their use of natural resources and other inputs to produce shrimp.

Conclusions

Economic outcomes improved with increased intensification of production that resulted in greater yields (metric tons per hectare). The greater yields spread annual fixed costs across greater production volumes and resulted in a decreased cost per metric ton of shrimp produced with increased intensification. Thus, within the range of yields and production systems included in this study, the more intensive production systems were more economically sustainable. Costs per metric ton of shrimp produced decreased from the lowest to the highest intensity levels for each species in each country (US$10,245/m.t. at lowest intensity to US$3484/m.t. at highest intensity for *P. monodon* and from US$24,301/m.t. [lowest intensity level] to US$5387/m.t. [highest intensity level] for *L. vannamei* in Vietnam and from US$8184/m.t. [lowest intensity level] to \$3817/m.t. [highest intensity level] for *L. vannamei* in Thailand).

In Vietnam, the least intensive production system was not profitable for either *P. monodon* or *L. vannamei* production. In Thailand, none of the clusters analyzed showed long-term profits. Annual fixed costs and labor costs were relatively higher in Thailand than in Vietnam. Careful attention needs to be paid to seek the most efficient ways to manage farms to improve long-term profitability in Thailand. Amendment costs were particularly high in Vietnam and included substances banned for use in aquaculture products. Moreover, in both Thailand and Vietnam, numerous other amendments not shown to be effective were used and increased production costs.

This analysis shows the importance of identifying groups of farms based on similar sets of management practices identified through multivariate analyses rather than on a single production parameter such as stocking density. Not accounting for important differences in farm management strategies other than stocking density can obscure important differences in economic outcomes.

This analysis has shown that more intensive shrimp production, using fewer resources per metric ton of shrimp produced, was also more economically sustainable than more extensive practices. On-farm research that incorporates economic effects into studies related to the sustainability and environmental management of aquaculture is needed to continue to provide useful guidance to farmers and policy makers.

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