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Comparative analysis of technical efficiency for different production culture systems and species of freshwater aquaculture in Peninsular Malaysia

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ABSTRACT

This study estimated the bias-corrected technical efficiency (BCTE) of different culture systems and species of freshwater aquaculture in Malaysia using bootstrapping data envelopment analysis (DEA). Data were collected from 307 respondents from three states in Peninsular Malaysia using a well-structured questionnaire as well as oral interviews. The findings indicate that all technical efficiency scores for all culture systems and species are below the optimal level (i.e. one). In addition, the results show that farmers' experience, contact with extension workers and household size have a positive and statistically significant impact on technical efficiency. This implies that farmers who have long tenure in fish farming and also the opportunity to meet with extension workers are operating close to the production frontier (technically efficient). On the other hand, the age of the farmers has a negative and statistically significant impact on technical efficiency. Although educational level and farm status have a positive impact on technical efficiency, they are statistically insignificant. Furthermore, all the inputs used in the production process of different culture systems and species contained slacks and need to be reduced accordingly. Feed, the major input in fish production and constituting over half of the production costs, is equally over-utilized. Thus, the government, in collaboration with research institutes and universities, should design a feeding formula for fish depending on species, culture systems and stages of growth. This could help to reduce production costs, increasing the farmers' income, as well as providing much needed animal protein to consumers at an affordable rate.

1. Introduction

Freshwater aquaculture, which has the potential to grow in Malaysia due to an abundance of natural resources, can play an important role in supplying protein to meet rising demand due to increases in consumers' income, changes in life style and population growth. In addition, freshwater aquaculture in Malaysia can be characterized as being very diverse, both in terms of culture systems and species. Catfish, carp, red tilapia, black tilapia, snakehead and prawn are produced in ponds, cages, ex-mining pools, cement tanks, canvas tanks, pens and many other systems. The total quantity of catfish produced in 2012 was approximately 73,816 tons, thereby making it the largest contributor to freshwater aquaculture production (47.08%). Another highly important species that has become increasingly vital in this sector is red tilapia, with total production of 38,841 tons (23.72%) in 2012. Carp species also play a significant role in freshwater aquaculture production, contributing 24,546 tons (14.99%). The contribution of black tilapia to freshwater aquaculture production accounted only for 12,713 tons (7.76%). Snakehead, giant freshwater prawn and other species contributed approximately 1,284 tons (0.78%), 318 tons (0.19%) and 12,239 tons (7.74%), respectively.

In terms of production culture systems, ponds are the major contributor of fish food to fresh water aquaculture, with total production of approximately 83,145 metric tons (63%) in 2013. This is followed by ex-mining pools, the production level of which dropped sharply from approximately 67,937 metric tons in 2012 to 32,582 metric tons in 2013. The next most important culture system is cages, which witnessed slight drop in production from 12,061 metric tons in 2012 to 10,854 metric tons (8.2%) in 2013. Cage culture systems involve the use of freshwater dams, lakes, reservoirs and—notably—abandoned ex-mining pools. However, as land becomes scarce and increasingly expensive due to urbanization and industrial use, cage culture systems are likely to attract

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Table 1
Description of the variables in DEA and OLS models.

Variables in the models	Description	Unit
Dependent variable		
Output	Total quantity of fish produced	Kilogram
Independent variables		
Stocking density	Fingerlings stocked in the farm per production cycle	Number
Feed	Total quantity of feed utilized per production cycle	Kilogram
Labor	Total number of family and hired labor used per production cycle	Man-day
Other costs	Represents costs incurred of other inputs per production cycle	Ringgit[a]
Technical efficiency determinants		
Age	Represents age of fish farmer/manager	Year
Experience	Represents number of years the farmer/manager spent in fish farming	Year
Educational level	Level of education of fish farmer/manager	Level
Farm status	Status of the fish farm and is dummy (1 = owner, and 0 = otherwise)	Dummy
Extension services	Extension visits to fish farm in the last three years (1 = yes; otherwise)	Dummy
Household size	Number of the fish farmer family	Number

[a] 1USD = 4.2 Ringgit (Malaysian currency).

more potential investors, thereby leading to an anticipated increase in production. Others culture systems, such as cement tanks, canvas tanks and pens, have played little role in contributing to freshwater aquaculture production. The total farmed food fish production from cement tanks, canvas tanks and pen culture systems in 2013 was approximately 4,827 metric tons (3.6%), 366 metric tons (0.3%) and 118 metric tons (0.1%), respectively.

Despite its wide diversification in terms of production culture systems and species, freshwater aquaculture production is relatively low compared to brackish water aquaculture. For instance, the total production from freshwater aquaculture in 2013 was a mere 132,892 metric tons (25%) compared to 397,313 metric tons (75%) from brackish water aquaculture. This low level of freshwater production could be attributed to technical inefficiency at the farm level. However, fish farmers may be facing different challenges in managing their farms and these may contribute directly or indirectly to technical inefficiency. Factors such as the farmer's age, experience, frequency of contact with extension workers, educational level, household size, farm status, access to credit facilities, adaptation of technology and water management techniques may be responsible for the technical inefficiency at farm level. Thus, it is against this background that the present study aims to estimate the technical efficiency of different culture systems and species in freshwater aquaculture. In addition, it aims to investigate those determinants that are responsible for technical inefficiency in freshwater aquaculture to formulate policy that will assist in improving this vital sector.

2. Efficiency measurement in aquaculture

There have been many theoretical developments in and practical applications of data envelopment analysis (DEA) since its invention, especially in the fields of banking, health, agriculture, transportation, education and manufacturing. Liu et al. (2013) reported that among the 4,936 published articles on DEA in citation journals, 1,802 (36.5%) and 3,134 (63.5%) are purely methodological and empirical applications, respectively. This wide application of DEA indicates its strength and capability in measuring the technical efficiency of firms.

However, stochastic frontier analysis (SFA) is predominantly used for estimating technical efficiency studies in the aquaculture industry (Appendix A), perhaps because DEA attributes all deviations from the production frontier to technical inefficiency, thereby making it an inappropriate technique in some sectors, especially in agriculture, in which the data collection process is sensitive to stochastic noise and other measurement errors (Coelli et al., 2005). This shortcoming of DEA led Simar and Wilson (1998, 2000) to propose a technique which allows the construction of confidence intervals for DEA technical efficiency scores with the help of bootstrapping procedures. The reason for bootstrapping is to estimate the bias-corrected technical efficiency (BCTE), which is more accurate estimates of efficiency scores than the conventional DEA.

Despite this development, the application of the DEA bootstrapping technique has thus far been limited in measuring the efficiency of aquaculture. Indeed, Chang et al. (2010) work is the only study to have used this technique to estimate BCTE in aquaculture. Most other studies have employed the conventional DEA model to estimate the technical efficiency of aquaculture (Appendix B). This therefore motivates the use of the DEA bootstrapping method to estimate BCTE in this study.

3. Methodology

This section presents the sampling technique, the method of data collection and the models employed in data analysis.

3.1. Sampling technique

Three states (Perak, Selangor and Pahang) of the 11 states in Peninsular Malaysia were purposively selected for this study based on two motives. First, they have the highest concentration of active pond fish farmers. Second, they produce a large share of fish in terms of freshwater pond aquaculture (41%). These states are further subdivided into clusters/districts using the cluster sampling method. Four, three and two districts were selected from Perak, Selangor and Pahang, respectively. The selection of districts was based on the large number of active fish farmers pertaining to particular culture systems present in these localities and their volume of production. Furthermore, a stratified sampling technique was employed to segregate the freshwater aquaculture from each selected area into strata, namely cages, ponds, tanks and pen cultures, to obtain a homogeneous distribution of the population. Finally, the sample respondents were then selected using simple random sampling from the list of freshwater fish farmers obtained from the Department of Fisheries, Malaysia.

3.2. Data collection

The data for this study were collected using a questionnaire and oral interviews with the selected fish farmers. Information was collected on their production input usage in a single production season, as well as the outputs produced. Initially, a pilot study was conducted to validate the questionnaire and all the necessary changes and adjustments were made. Subsequently, a total of 307 questionnaires were finally administered to the selected fish farmers, but only 212 observations were used for the analysis in this study due incomplete responses by some farmers (36). The valid responses consisted of 57, 66, 69 and 20 decision-making units (DMUs) for tanks, ponds, cages and pen culture systems, respectively

3.3. Analytical technique

Two-stage DEA was employed using first estimate technical efficiency scores and then regressing the estimated technical efficiency scores against socioeconomic and farm-specific variables. This procedure yields significantly better results than either single-stage or double-stage SFA that assumes either Cobb-Douglas or translog functional forms (Banker and Natarajan, 2008). Although most of the previous studies used the Tobit regression model (TRM) in the second stage (Alam, 2011; Cinemre et al., 2006; Kaliba et al., 2007), McDonald (2009) argued that its use is considered inappropriate in this situation. According to McDonald (2009), technical efficiency scores are fraction data and not generated by a censoring process; instead, McDonald (2009) suggested the use of an ordinary least squares (OLS) regression model as the most appropriate technique. This argument was supported by Banker and Natarajan (2008). They reported that the use of OLS regression analysis in the second stage of DEA gives better results than using TRM because it gives statistically consistent estimators of the influence of contextual factors.

3.4. Model specification

3.4.1. Data envelopment analysis (DEA)

Notwithstanding the above, as fish farmers have more control over their inputs than outputs, the DEA input-oriented model was adopted for the study to estimate technical efficiency. The model is expressed as follows:

$$\min_{\theta_i \lambda_j} \theta_i$$

st :

$$y_{ri} - \sum_{j=1}^{n} Y_{rj}\lambda_j \le 0, r = 1, \ldots\ldots\ldots, s$$

$$\theta_i x_{ik} - \sum_{j=1}^{n} X_{kj}\lambda_j \ge 0, k = 1, \ldots\ldots\ldots\ldots, m$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \ge 0, j = 1, \ldots\ldots\ldots\ldots\ldots, n \qquad (1)$$

where θ_i denotes the technical efficiency of the i-th fish farm, this i-th fish farms uses m inputs set x_{ik} (m represents stocking density, feed, labour, costs of other relevant inputs) to produces s output set y_{rj} (s represents different types of fish products); m is the number of inputs ($i = 1\ldots m$); s is the number of outputs ($r = 1\ldots s$); n is the number of fish farms ($j = 1\ldots n$); λ_j is a nonnegative vector that permits the construction of a production possibility set for j DMU; Y_{rj} is a vector of output level; X_{kj} is a vector of observed inputs (Coelli et al., 2005).

3.4.2. Efficiency effects analysis

The second stage of the analysis followed Banker and Natarajan (2008). The model can be expressed as follows:

$$\mathrm{BCTE} = \beta_0 = \sum_{i=1}^{n} \beta_i z_i + \delta \qquad (2)$$

where BCTE denotes bias-corrected technical efficiency and β denotes unknown parameters to be estimated. Z denotes the socioeconomic variables and farm characteristics defined in Table 3, while δ is the error term.

Table 2
Estimated bias technical efficiency (BTE) and bias-corrected technical efficiency (BCTE).

Culture systems/species	Mean values			Confidence interval (95%)	
	BTE	BCTE	Bias	Lower	Upper
Aquaculture	0.85	0.80	0.05	0.7884	0.813
Ponds	0.86	0.77	0.09	0.7367	0.8031
Cages	0.87	0.80	0.07	0.7702	0.8197
Tanks	0.88	0.77	0.11	0.736	0.8078
Pen culture	0.83	0.63	0.20	0.564	0.6964
Polyculture	0.83	0.71	0.12	0.6919	0.7438
Patin	0.89	0.79	0.10	0.7402	0.8313
Tilapia	0.85	0.74	0.11	0.705	0.7791
Catfish	0.88	0.80	0.09	0.776	0.824

3.5. Definition of Variables

In this study, one output and four inputs were used to measure technical efficiency. The output represents the quantity of fish produced by farmers, measured in kilogrammes. The optimal measure of output for polyculture would have been the geometric mean or quantity index based on revenue share or the prices of different species of fish. However, data on the prices of different species were not available and thus we used total fish production as a proxy for output (Iinuma et al., 1999). Inputs included stocking density, feed, labour and costs of other relevant inputs as illustrated in Table 1. The stocking density is measured as the number of juvenile fish stocked. The feed variable is measured as the quantity of feed used, in kilogrammes. The labour variable represents the number of hours spent working on farms, measured in man days. Other costs include the sum of chemicals, repairs, fuel, telephone calls and other miscellaneous expenses. Asche and Roll (2013), in their study of the determinants of inefficiency in Norwegian salmon aquaculture, also used fish produced as output, with stocking density, feed, labour and capital used as inputs. In addition, Iinuma et al. (1999) estimated the technical efficiency of carp pond culture in Peninsular Malaysia using total production to represent output, while feed, stocking density, labour and other expenses were included as inputs. Table 1 also shows the variables used to investigate the determinants of technical efficiency in freshwater aquaculture.

4. Results and discussion

4.1. Estimates of technical efficiency

The study estimated bias corrected technical efficiency (BCTE) using bootstrapped DEA (Table 2). The estimated mean BCTE for the sample fish farmers was 0.80, which implies that the fish farmers in the sample could reach full technical efficiency by increasing their outputs by another 20% with the current level of technology and input levels. The fish farms were further divided into two subsectors based on species types and culture systems to develop in-depth analysis of the industry's performance. The estimated mean BCTE values of different species, catfish, tilapia, patin and polyculture, were 0.71, 0.79, 0.74 and 0.80, respectively (Table 2). Based on these findings, the polyculture and Tilapia farms were the most technically efficient, whereas the least efficient ones—on average—were the catfish and patin farms. Polyculture fish farms are mostly large and culture many species in the same place and thereby take advantage of economies of scale. On the other hand, catfish are mostly cultured using an extensive technique in which they largely depend

Table 3
Test of statistically differences between BTE and BCTE.

Culture Systems/species	Mean values ± standard deviation BTE ± SD	BCTE ± SD	*P*-value
Aquaculture	0.85 ± 0.08^a	0.80 ± 0.08^b	0.0001
Ponds	0.86 ± 0.12^a	0.77 ± 0.1^b	0.0014
Cages	0.87 ± 0.13^a	0.80 ± 0.12^b	0.0003
Tanks	0.88 ± 0.14^a	0.77 ± 0.1b	0.0001
Pen culture	0.83 ± 0.21^a	0.63 ± 0.06^b	0.002
Polyculture	0.83 ± 0.15^a	0.71 ± 0.10^b	0.001
Patin	0.89 ± 0.16^a	0.79 ± 0.12^b	0.01
Red tilapia	0.85 ± 0.15^a	0.74 ± 0.10^b	0.001
Catfish	0.88 ± 0.10^a	0.80 ± 0.06^b	0.0003

Note: Means ± SD within the same raw with different superscripts(a and b) are statistically significant at $P < 0.05$.

Table 4
Slacks variable for different types of culture systems.

Culture systems	Input slacks (%)			
	Seed	Feed	labour	Other costs
Aquaculture	0.056	9.000	1.516	6.571
Ponds	0.020	8.656	0.788	2.813
Cages	2.089	2.063	4.720	1.623
Tanks	4.029	1.916	3.450	3.410
Pen culture	4.962	9.186	1.029	3.046
Total	11.156	30.821	11.503	17.463

Table 5
Determinants of technical inefficiency in freshwater aquaculture.

Variables	Coefficient	Standard error	*T*-value	*P*-value
Experience	−0.0032519	0.0017829	−1.83	0.070
Age	0.0009327	0.0004936	1.89	0.061
Extension visits	−0.0616676	0.0216327	−2.85	0.005
Education	−0.0091106	0.0071224	−1.28	0.203
Family size	−0.0036466	0.0020576	−1.77	0.078
Farm status	−0.0033831	0.0165511	−0.2	0.838

on natural foods that may sometimes be scarce due to overexploitation.

Furthermore, the estimated BCTE values of the various culture systems, cages, ponds, tanks and pens, were found to be 0.80, 0.77, 0.77 and 0.63, respectively. More or less, all the results show that the fish farms were relatively inefficient, implying that there is still room for substantial improvements in technical efficiency while maintaining the current input levels and existing production technology. Fish grow-out in cages was the most technically efficient process, while the least efficient system on average was pen cultures. This is perhaps because cage culture is mostly practised as an intensive system in which food is frequently supplied to the fish. In addition, the cage culture environment is largely free from contamination due to the large water bodies involved, coupled with the availability of natural food, making this system more efficient than ponds, tanks and pen cultures. Pen cultures are small in size and this in general affects the efficiency of the fish culture in this system, perhaps because they do not benefit from economies of scale.

Table 3 shows the comparison of mean differences between BTE and BCTE. The results revealed that statistically significant differences exist between estimated values of BTE and BCTE in all culture systems and species under consideration. Similarly, Chang et al. (2010) reported statistically significant difference between mean BTE and BCTE of aquaculture firms in Taiwan. This implies the use of BCTE is more robust compared to BTE especially in aquaculture. Therefore, the following discussion of slack variables was based on the BCTE.

4.2. *Slack variables analysis*

A slack variable simply refers to excess or deficit of input(s) used in the firm production operation, measured as a percentage. Feed is one of the most important components of fish farming and constitutes the highest percentage of input costs in many fish farms (Alam, 2011). The estimated percentages of feed slacks for ponds, cages, tanks and pen cultures were 9.0, 2.06, 1.91 and 9.2, respectively (Table 4). This implies that fish farmers using ponds, cages, tanks and pen cultures could operate on the production frontier by reducing their feed levels by 9.0%, 2.06%, 1.91% and 9.2%, respectively. Although the feed slacks for tank and cage cultures are much lower than for ponds and pen cultures, the majority of the sample fish farms operate on a small scale and lack a standard feed formula. Thus, they usually depend on their experience to feed the fish, leading to inefficient use of this input. However, the implications of over-feeding are twofold. First, this practice increases the production costs, leading to low revenue for farmers. Second, the excess feeds may pollute the fish habitat, thereby reducing the oxygen contained in the water and subsequently causing a high mortality rate.

The findings estimate the percentages of seed slacks to be 0.02, 2.089, 4.029 and 4.962 for ponds, cages, tanks and pen cultures, respectively. This means that seed inputs could be reduced by 0.02%, 2.089%, 4.029% and 4.962% without changing the output levels for ponds, cages, tanks and pen cultures, respectively. Based on these findings, the stocking rate is an obstacle in tanks and pen cultures but not in ponds and cage cultures. Ponds and cages are usually large in size and can therefore accommodate large fish stocks. However, tanks and pen cultures are usually small and any increase in the stocking rate beyond the reasonable level will have adverse effects on the outputs.

The majority of the fish farmers in this study are operating at the small-scale level. They largely depend on family labour and sometimes hire one or two casual workers during harvesting or fish farm preparation. The results show that the percentages of labour slacks for ponds, cages, tanks, and pen cultures to be 0.78, 4.7, 3.5 and 1.0, respectively. This indicates that labour input could be reduced by 0.78%, 4.7%, 3.5% and 1.0% and still be able to produce the same output levels for ponds, cages, tanks and pen cultures, respectively. Therefore, all the culture systems, except cages, require little adjustment to achieve labour efficiency. Cage fish farming is mostly done in rivers and therefore requires much more labour, especially during harvest and reinforcement of the cages. The slacks of the other cost variables for ponds, cages, tanks and pen culture systems were relatively low and hence require only small adjustments.

4.3. *Technical inefficiency analysis*

Table 5 shows the determinants of technical inefficiency in freshwater aquaculture. The study used inefficiency as the dependent variable and hence those variables with a negative (positive) coefficient sign will have a positive (negative) impact on technical efficiency. The coefficient of farmers' experience was found to be negative and statistically significant. This implies that experienced fish farmers are more technically efficient. Most experienced farmers have acquired skills over time due to frequent contact with extension workers. This finding is supported by the coefficient of the extension service variable in the model which has a negative sign and is statistically significant. Fish farmers who receive extension services are more efficient, perhaps because they can easily learn about new or improved technology.

Furthermore, the coefficient of family size has a negative sign and is statistically significant. Fish farmers in most rural areas are poor and thus cannot afford to own modern machinery. Therefore, they largely depend on manual labour for their farm operations.

As a result, the larger the family size, the more likely they are to be efficient in input usage. Contrary to expectations, the sign of the coefficient of the age variable is positive and it is statistically significant. This may be due to the conservative nature of older fish farmers, meaning that they are less willing to adopt new or improved technology and thereby having low technical efficiency in production. The negative coefficient of the education variable implies that fish farmers with a higher educational level tend to be more technically efficient. However, this relationship is statistically insignificant because the estimated coefficient is relatively small compared to its standard error. Although the coefficient of farm status has a negative sign, it is statistically insignificant. Most of these findings are consistent with most previous studies, as illustrated in the Appendix C.

5. Conclusion

This study estimated the bias-corrected technical efficiency (BCTE) of different culture systems and species for freshwater aquaculture. Among the four culture systems study, cage fish farming is the more efficient with BCTE score of 0.80. On the other hand, catfish is the most efficient species with BCTE score of 0.80 too. Generally, BCTE results show that all the fish farmers in the study sample are operating below the production frontier. Hence, the need to investigate the sources of this technical inefficiency by regressing the estimated BCTE values against some farmers' socioeconomic variables and farm characteristics. The results indicate that farmers' experience, contact with extension workers and household size have positive and statistically significant impact on technical efficiency. This implies that farmers who have long tenure in fish farming and also the opportunity to meet with extension workers are operating close to the production frontier (technically efficient). Although educational level and farm status have a positive impact on technical efficiency, they are statistically insignificant. On the other hand, the age of the farmers has a negative and statistically significant impact on technical efficiency. Those farmers who are older may be conservative and refrain from adopting new or improved technology. They may also have invested in a particular production technology which makes it difficult to change to a new or improved technology and therefore are less technically efficient. Based on these findings, efforts should be geared toward educating fish farmers about new or improved technology through organizing training and workshops by extension workers. Experience fish farmers should be encouraged to share their fish farming knowledge with new and young ones in order for them to catch-up or increase efficiency level.

Furthermore, all the inputs used in the production processes of different culture systems and species contain slacks, which need to be reduced accordingly. Feed, being the major input in fish production and constituting over half of the production costs, is equally over-utilized. Thus, the government, in collaboration with research institutes and universities, should design a feeding formula for fish depending on the species, culture system and stage of growth. This could help reduce feed wastage or production costs, increasing the farmers' income and providing much needed animal protein to consumers at an affordable rate. In addition, this may serve as a potential approach to minimise the water population as well as improve water quality.

The study suffers from certain limitations. The paper attempts to investigate the determinants of technical inefficiency in freshwater aquaculture using only six variables. Future research should consider including more factors which may have an impact on technical inefficiency, such as skills in water management, mortality rate, government subsidies, technological adaptation, access to credit facilities and farm size. In addition, future research should conduct in depth analysis by investigating the sources of technical inefficiency for each culture system and species. Despite its limitations, however, the study contributes to the existing literature on technical efficiency in aquaculture.

Appendix A. : SFA applications in aquaculture

Author(s)/Year	Country	Method	Production technology	TE
Iliyasu et al. (2016)	Malaysia	SFA	Cage fish farming	0.79
Asche and Roll (2013)	Norway	SFA	Salmon	0.82
Begum et al. (2013)	Bangladesh	SFA	Shrimp	0.82
Tsue et al. (2013)	Nigeria	SFA	Catfish farms	0.82
Alam et al. (2012)	Bangladesh	SFA	Tilapia	0.78
Tan et al. (2011)	Philippines			
	Sampaloc lake	SFA	Tilapia	0.18
	Palakpakin lake	SFA	Tilapia	0.28
	Laurel lake	SFA	Tilapia	0.39
	Agoncilla lake	SFA	Tilapia	0.46
Onumah et al. (2010)	Ghana	SFA	Fish farms	0.84
Onumah and Acquah (2010)	Ghana	SFA	Fish farms	0.81
Kareem et al. (2009)	Nigeria	SFA	Concrete ponds	0.88
		SFA	Earthen ponds	0.89
Singh et al. (2009)	India	SFA	Fish farms	0.66
Ferdous Alam and Murshed-e-Jahan (2008)	Bangladesh	SFA	Prawn-carp	0.85
Roy and Jens (2008)	India	SFA	Fish farms	0.73
Singh (2008)	India	SFA	Fish farms Category I[1]	0.69
		SFA	Fish farms Category II[2]	0.65
Amos (2007)	Nigeria	SFA	Crustacean farms	0.7
Den and Ancev Haris (2007)	Vietnam		Prawn farming	
		SFA	Intensive	0.71
		SFA	Extensive	0.47
Dey et al. (2000)	China	SFA	Extensive/semi-intensive	0.77
		SFA	Intensive/semi-intensive	0.84
		SFA	Intensive	0.93
	India	SFA	Intensive/semi-intensive	0.86
		SFA	Extensive	0.65
	Thailand	SFA	Extensive	0.72
		SFA	Intensive/semi-intensive	0.91
	Vietnam	SFA	Extensive	0.42
		SFA	Intensive/semi-intensive	0.48

Kumar et al. (2004)	India	SFA	Shrimp farms	0.69
Arjumanara et al. (2004)	Bangladesh	SFA	CTR^{3}	0.69
		SFA	TR^{4}	0.86
		SFA	TCNR^{5}	0.61
Chiang et al. (2004)	Taiwan	SFA	Milkfish farms	0.82
Irz and Mckenzie (2003)	Philippine	SFA	Freshwater fish farms	0.83
		SFA	Brackish water fish farms	0.54
Awoyemi et al. (2003)	Nigeria	SFA	Fish farms	0.24
Sharma and Leung (2000)	India	SFA	Carp	0.66
Sharma (1999)	Pakistan	SFA	Carp	0.56
Iinuma et al. (1999)	Malaysia	SFA	Carp	0.24
Sharma and Leung (1998)	Nepal	SFA	Carp	0.69
Gunaratne and Leung (1997)	Malaysia	SFA	Shrimp	0.78
Mean				**0.68**

[1] Pond area ≤0.32 acre.
[2] Pond area >0.32 acre.
[3] Technical advice receiving farmers.
[4] Training receiving farmers.
[5] Normal farmers.

Appendix B. : DEA applications in aquaculture

Author(s)/Year	Country	Method	Production technology	TE
Nguyen and Fisher (2014)	Vietnam	CDEA	Shrimp	
			Intensive	0.53
			Semi-intensive	0.7
			Extensive	0.31
Arita and Leung (2014)	Hawaii			
		CDEA	Aquaculture farms^{1}	0.73
		CDEA	Aquaculture farms^{3}	0.46
		CDEA	Catfish^{1}	0.96
		CDEA	Catfish^{3}	0.52
		CDEA	Foodfish^{1}	0.56
		CDEA	Crustacean^{3}	0.36
		CDEA	Crustacean^{3}	0.37
		CDEA	Ornamental^{1}	0.85
		CDEA	Mollusks and Others^{1}	0.57
Alam (2011)	Bangladesh	CDEA	Pangas Fish farms	0.86
Nielsen (2011)	Denmark	CDEA	Salmon	0.81
Chang et al. (2010)	Taiwan	BDEA	SPUG^{4}	0.55
		CDEA	SPNUG^{5}	0.52
		CDEA	NSPUG^{6}	0.4
		CDEA	NSPNUG^{7}	0.25
Cinemre et al. (2006)	Turkey	CDEA	Trout farms	0.82
Kaliba and Engle (2006)	USA	CDEA	Catfish farms	0.73
Sharma et al. (1999)	China	CDEA	Carp	0.83
Gunaratne and Leung (1997)	Malaysia	CDEA	Shrimp	0.8
Mean				**0.61**

*Conventional Data Envelopment Analysis.
¶Bootstrapping Data Envelopment Analysis.
[1] 1997.
[2] 2002.
[3] 2007.
[4] Shellfish producer using groundwater.
[5] Shellfish producer not using groundwater.
[6] Non Shellfish producer using groundwater.
[7] Non Shellfish producer non using groundwater.

Appendix C. : Impact of Farm- specific variables and socio-economic factors on Technical Efficiency

Author(s)/Year	Country	Method	Farm characteristics and socio-economic-factors
Asche and Roll (2013)	Norway	SFA	Age(−)***; Disease(−)*; Insurance disbursement(−)*: Lack of smolt(−)*; Salmon price(−)*
Begum et al. (2013)	Bangladesh	SFA	Age(+)*; Education(+)***; Non-farm-income(+)*;Distance(−)*;Family size(−);tenureship(+);Water qualityr(−);
Tsue et al. (2013)	Nigeria	SFA	Age(+)**; Education(+)*;Experience(+); Household size(+)***
Alam et al. (2012)	Bangladesh	SFA	Age(+)*; Education(+); Income(−)*;Culture length(+)**;Depth of pond(+);Pond age(+);Water color(+)
Alam (2011)	Bangladesh	DEA	Age(−); Experience(−);Culture length(−);Fry size(−)*
Tan et al. (2011)	Philippines		
	Sampalok lake	SFA	Age(−);Education(−)**;Experience(−);Fry price(+)*;Culture length(−)*;Farm size(−);Cage area(−);Mortality(−)**
	Palakpakin	SFA	Age(+);Education(+);Experience(+);Fry price(+)*;;Farm size(−);Cage area(−); Depth of cage(−);Mortality(−)*
	Laurel	SFA	Age(−);Education(−);Experience(+);Fry price(+);Culture length (+);Farm size(+)**;Mortality(−)**;
	Agoncillo	SFA	Age(+);Education(+)**;Experience(+);Fry price(+);Farm size(−)**;Depth of cage(+); Mortality(−)**
Onumah et al. (2010)	Ghana	SFA	Age(−)*;Education(−)**;Experience(−)*;;Gender(+)*;Pond type(+)*;Extension services(+)**Occupation status(+)*
Onumah et al. (2010)	Ghana	SFA	Age(−);Education(−);Experience(−)*;Gender(+)*;Pond type(+)*;farm size(−)*

Kareem et al. (2008)	Nigeria		
	Earthen pond	SFA	Age(−);Education(+);Experience(+); Household size(+)
	Concrate pond	SFA	Age(−);Education(+);Experience(+)*;Household size(+)
Singh et al. (2009)	India	SFA	Education(+)*;Experience(−)**; Technical training (+); Source of fingerlings (+)*
Roy and Jens (2008)	India	SFA	Age(+);Education(+);Experience(−);Pond size(+)**;Water Source(+)**; Period netting for biomass(−)**
Amos (2007)	Nigeria	SFA	Age(−)**; Education(−); Household size(+)**
Cinemre et al. (2006)	Turkey	DEA	Education (+); Experience (+)**; Pond size (−)*;Pond tenure (+)**; Access to credit (+)*Extension Services (+)
Mohan Dey et al. (2005)	China		
	Extensive	SFA	Experience (+); Farm Size (−); Distance from market (−)
	Semi-extensive	SFA	Experience (−);Farm Size (+)*;Distance from market (−)
	Intensive	SFA	Experience(+);Farm Size(+)**;Distance from market (+)
	India		
	Semi-extensive	SFA	Age(−); Education(+); Farm Size (−); Tenure(+);Distance from market (−)
	Extensive	SFA	Age(−); Education(+)*; Farm Size (−)*; Tenure(+)*;Distance from market (−)
Chiang et al. (2004)	Taiwan	SFA	Education(−)*; Experience(−)**;
Irz and Mckenzie (2003)	Philippines		
	Freshwater	SFA	Experience(+);Farm size(−);pond quality(+)*;Number of Production cycle/year(+)**
	Brackish water	SFA	Experience(+)*;Farm size(−);Manager's visit(+)*;Number of Production cycle/year(+)**

[*] Significant at 1% level.

[**] Significant at 5% level.

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