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Economic-environmental trade-offs in marine aquaculture: The case of lobster farming in Vietnam

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ABSTRACT

Marine aquaculture has increased in importance in most countries over recent decades. In order to develop this sector in a sustainable way, it is necessary to consider its environmental impacts. In Vietnam, marine cage lobster cultivation has been seen as a high return business. However, in recent years, the sector has been facing sustainability issues, with recurrent disease outbreaks and increased lobster mortality. These phenomena are linked to nutrient pollution, which is attributed to the overuse of feed inputs. The annual loss for the sector is reported to be up to 30 million USD. Local lobster farmers have reacted to these issues by spending more on antibiotics and chemicals, or by increasing efforts to clean cages. This behavior suggests that farmers perceive a conflict between reducing environmental pressure and improving the economic performance of the sector. In order to identify the relationship between cost and environmental efficiency, this paper uses a Material Balance Principle based Data Envelopment Analysis approach using a dataset of 353 marine cage lobster farms in Vietnam. The findings show that improvements in input use efficiency would result in both lower production costs and better environmental performance. If lobster farms were to become more cost efficient, using a more appropriate input mix, given the input price information, this would benefit the environment. Similarly, improving environmental performance generally also reduces production costs.

1. Introduction

In recent decades, increasing demands for fish products and leveling–off of fisheries' landings have led to a substantial growth in the importance of marine aquaculture (Marra, 2005; Tovar et al., 2000). In 2016, the production from marine aquaculture was28.7 million tons and accounted for 36% of global aquaculture production (FAO, 2018). Asia was the main contributor of the sector with 82.9% (23.8 million tons) (FAO, 2018). Also, experts predict that, in the future, a large proportion of growth in the aquaculture sector will occur in marine waters (Davies et al., 2019; FAO, 2016; Marine Aquaculture Task Force, 2007). At the same time, there are increasing concerns about the environmental impacts of the sector (Ahmed and Thompson, 2018; Farmaki et al., 2014; Gu et al., 2017; Olaussen, 2018; Read and Fernandes, 2003) and several authors have used Life Cycle Assessments to try to capture one or more of the environmental impacts (Dekamin et al., 2015; Pérez-López et al., 2017; Seghetta et al., 2016).

Nevertheless, research linking economic performance with the environmental impacts of marine aquaculture is scarce. Without adequate information it is difficult for policy makers to balance the potential benefits of the sector and its effects on the environment. Therefore, in order to develop marine aquaculture in a sustainable manner, environmental efficiency and the economic-environmental trade-offs of this industry should be investigated.

Vietnam, with its long coastline, many islands and bays, has great potential for marine aquaculture development (Minh et al., 2016; Tuan, 2011). Since 1992, lobster has been one of the common marine cultures in this country (Petersen and Phuong, 2011; Tuan, 2011). Marine cage lobster farming is not only an important economic activity, but it also has a significant positive impact on the livelihoods of the impoverished coastal communities in Vietnam (FAO, 2011; Minh et al., 2016; Petersen and Phuong, 2010). However, in recent years, outbreaks of disease and increased lobster mortality have been major constraints for Vietnamese lobster farms (FAO, 2011; Minh et al., 2016; People's Committee of Phu Yen province, 2017). These problems might be related to factors such as stocking density, farm size, the species cultivated or specific farming practices (Ton Nu Hai et al., 2018, 2017). However, the factor that is primarily held responsible is the nutrient pollution problem originating from the overuse of trash fish as feed for the lobsters. The overuse of feed leads to a large input of organic matter

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into the marine environment (Asche et al., 2009; FAO, 2011; Hoang et al., 2009; Hung et al., 2010; Lee et al., 2015a, 2015b; Minh et al., 2016; Tovar et al., 2000). Estimates of the nitrogen loadings released into the marine environment to produce one ton of lobster ranges from 204 to 389 kg (An and Tuan, 2012; Chien, 2005; Ly, 2009). The environmental problems created by the nutrient surplus have been reported by several authors (Hung et al., 2010; Lee et al., 2015a, 2015b; Wu, 1995). The high nutrient concentrations can lead to eutrophication in the farming area and cause algal bloom. This results in lower oxygen levels. The poorer water quality increases stress and makes the lobsters more susceptible to diseases, increasing lobster mortality (FAO, 2011; Hung and Tuan, 2009; Tuan, 2011). In this way, the overuse of feed obviously has negative feedback effects on lobster productivity (Asche et al., 2009; Asche and Tveteras, 2005; FAO, 2011; Hung and Tuan, 2009; Minh et al., 2016; Tuan, 2011; Tveterås, 2002). In the past decade, mortality in lobster farming has increased from 30% to 50%, representing an annual loss of 30 million USD. Rather than opting to use less feed, local lobster farms seemed to address the issue by increasing the cleaning frequency for lobster cages (Ton Nu Hai et al., 2018) and by increasing their expenditure on antibiotics and chemicals to treat disease (Hedberg et al., 2018). These strategies seem to suggest that farmers perceive pollution reduction to be costly and that this would reduce economic efficiency, implying the existence of a negative economic-environmental trade-off (Van Meensel et al., 2010b) in lobster farming in Vietnam. However, reducing environmental pressure is not always associated with lower economic outcomes and vice versa. Cagno et al. (2005) have shown that increasing input efficiency can reduce or eliminate the generation of pollutants and Asmild and Hougaard (2006) concluded that sizeable environmental improvements can be attained without any cost. Some other studies have even shown that both economic and environmental objectives can be achieved simultaneously by using inputs more efficiently (Thanh Nguyen et al., 2012; Van Meensel et al., 2010a, 2010b; Welch and Barnum, 2009). This can be called a positive economic-environmental trade-off (Van Meensel et al., 2010b).

In order to provide farms with better guidance about reducing nutrient pollution and improving economic performance, and to assist policy makers in making informed policy decisions that promote sustainable development, this paper examines economic-environmental trade-offs, focusing on nutrient pollution for the case of lobster farms in Vietnam. Using a Material Balance Principle (MBP) based Data Envelopment Analysis (DEA) approach we investigate whether the cost efficiency of marine aquaculture really deviates from environmental efficiency and what the effect of using inputs more efficiently will be on the economic and environmental performance of the farms. The economic-environmental trade-offs caused by moving from the current situation to cost efficient or to environmentally efficient operations are explored, as well as those arising from moving from cost efficient to environmentally efficient operations, and vice versa.

2. Research methodology

2.1. Empirical studies on economic–environmental trade-offs

Economic-environmental trade-off refers to the relationship between economic and environmental performance. In this study, the economic-environmental trade-offs consider the effect on economic performance of improving environmental performance or the effect on environmental performance of improving economic performance. Because this study assumes that environmental performance is related to the nutrient emission of the production, the environmental objective is to minimize this emission without changing the output. Traditionally, economic performance and environmental performance are believed to have a conflicting relationship. The idea of “it pays to be green” (Telle, 2006) implies that there is a certain cost attached to improving environmental performance or, in other words, that a negative economic-environmental trade-off exists (Van Meensel et al., 2010b). However, several recent studies (Cagno et al., 2005; Thanh Nguyen et al., 2012; Van Meensel et al., 2010a, 2010b; Welch and Barnum, 2009) have proved that a positive relationship can exist between economic performance and environmental performance, implying a positive economic-environmental trade-off.

In recent decades, many studies have considered either the relationship between economic and environmental performance or the economic-environmental trade-offs of different types of production under various circumstances using various methodologies. For example, Galdeano-Gómez et al. (2008) and Galdeano-Gómez and Céspedes-Lorente (2008) used a regression method to investigate the effects of environmental performance on agricultural productivity. Nishitani et al. (2017) used a similar approach to discuss the relationship between the environmental and economic performance of a number of industries. Pekovic et al. (2018) used a fixed-effects model to look at the effects of environmental investments on the economic performance of firms belonging to the manufacturing sector. Beaumont and Tinch (2004) used abatement cost curves to identify the barriers of a win-win state for copper pollution. Lynch et al. (2018) used the Farmscoper tool to identify the correlation between the environmental efficiency and profitability of agricultural systems. However, these studies only indirectly mention the trade-off between economic and environmental performance. To measure the economic-environmental trade-offs, the studies by Kataria et al. (2010), Li et al. (2013), and Wang et al. (2016) applied a chance constrained programming method[1] in the case of water pollution due to agricultural production, chemical industry and other activities. A weakness of this approach is that a functional form for the distribution of the environmental variable needs to be specified when applying this method (Matthews and Grové, 2017; Qiu et al., 2001). The Target MOTAD (minimization of total absolute deviations) approach used in the studies by Qiu et al. (1998) and Teague et al. (1995) for estimating the economic-environmental trade-offs in the case of crop production deals with this weakness of the chance constrained programming method (Matthews and Grové, 2017; Qiu et al., 2001). Another alternative is the Upper Partial Moment method (Qiu et al., 2001). However, Matthews and Grové (2017) showed that the application of this method can lead to biased results because it is too conservative and they introduced the upper frequency method. Based on the direct link between pollutants and nutrient content in inputs, some studies have used data envelopment analysis (DEA) or combined DEA with the material balance principle to identify the economic-environmental trade-off. There are applications for crop production (Aldanondo-Ochoa et al., 2017; Thanh Nguyen et al., 2012), pig production (Asmild and Hougaard, 2006; Van Meensel et al., 2010a, 2010b), and for the electricity industry (Welch and Barnum, 2009). However, only a few studies have directly measured the value of the trade-off (Thanh Nguyen et al., 2012; Welch and Barnum, 2009). Moreover, none of the above studies focused on aquaculture, although this sector is increasing in importance and negative environmental impacts are widely reported. Because of the direct link between nitrogen, as a polluting output, and its content in the inputs used, this paper applies the Material Balance Principle in a Data Envelopment Analysis framework to fill this gap and to measure the economic-environmental trade-off of marine aquaculture in Vietnam.

2.2. Material balance principle

There have been many studies (see review by Reinhard, 1999; Song et al., 2012; Tyteca, 1996; Zhou et al., 2018; Lauwers, 2009) that introduced environmental effects as either a bad output or an environmentally detrimental input into a production function when

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[1] Chance constrained programming is a method first introduced by Charners and Cooper (1963) to solve optimization problems under uncertainty.

measuring environmental efficiency (Aldanondo-Ochoa et al., 2014; Ball et al., 1994; Berre et al., 2014; Fare et al., 1996, 1989; Hailu and Veeman, 2001; Pittman, 1983; Reinhard et al., 2000; Tyteca, 1997; Yaisawarng and Klein, 1994). This approach can give results that are inconsistent with the material balance principle (Coelli et al., 2007; Hoang and Coelli, 2011) which is based on the rule of "what goes in must go out" in mass conservation. It is, therefore, inappropriate to apply this traditional approach to measure the environmental efficiency of marine cage lobster aquaculture in Vietnam. Coelli et al. (2007) were the first to propose an alternative and to base the measurement of environmental efficiency on the material balance principle. This approach has been called a "Materials balance-based approach" (Hoang and Nguyen, 2013; Lauwers, 2009) and has been applied, for example, to the Belgian pig-finishing sector. In contrast with previous studies, under the Material balance-based approach, environmental effects are not introduced as additional variables into the production model. The approach has been further refined by Ramilan et al. (2011) and Aldanondo-Ochoa et al. (2017). In recent years, it has been applied in a number of studies considering agricultural production (Aldanondo-Ochoa et al., 2017; Hoang and Alauddin, 2012; Hoang and Coelli, 2011; Hoang and Nguyen, 2013; Lauwers, 2009; Thanh Nguyen et al., 2012; Van Meensel et al., 2010a, 2010b) and for other production activities (Welch and Barnum, 2009). Because in the case of marine cage lobster aquaculture there is a clear direct link between nitrogen pollution and the nutrient content in inputs it is suitable to use a material balance based DEA approach to measure environmental efficiency and to identify economic-environmental trade-offs.

The transformation of materials in agricultural production is regulated by the Materials balance principle. This implies that the nutrient loss or emission equals the amount of nutrients contained in the inputs minus the nutrients contained in the output.

Consider the case of n farms or decision making units (DMUs). Each farm uses K inputs (x) to produce M conventional outputs (y). An emission of polluting substance (z) is also related to this production. The amount of emission is the balance of nutrients based on the Material balance principle is given in equation (1):

$$Z = a'x - b'y \tag{1}$$

where a and b are the nutrient contents in the inputs and outputs. It is possible that some inputs have zero nutrient content. Therefore, the vectors a for those inputs may include zero values.

2.3. Cost and environmental efficiency using bootstrap data envelopment analysis (DEA)

Data envelopment analysis is a method that measures the relative efficiency of DMUs by constructing a frontier based on the most efficient combinations of input and output. With the goal of production at the lowest cost, the DEA model for defining cost minimization is given in equation (2).

$$\begin{aligned} & Min_{\lambda,x_i^{CE}} w_i' x_i^{CE} \\ \text{Subject to} \quad & -y_i + Y\lambda \geq 0, \\ & x_i^{CE} - X\lambda \geq 0, \\ & \textstyle\sum_{i=1}^{N} \lambda_i = 1 \\ & \lambda \geq 0 \end{aligned} \tag{2}$$

where x_i^{CE} is the input quantity that minimizes the cost, w_i is a vector of input prices and λ is a vector of constant.

The cost efficiency (CE) is then equal to the minimum cost divided by the observed cost:

$$CE = w_i' x_i^{CE} / w_i' x_i \tag{3}$$

For measuring environmental efficiency, the emission (z) released to the marine environment in lobster production, shown in equation (1), was considered as pollution in this study. This means that a farm will be environmentally efficient if it can produce its level of output minimizing pollution. This pollution will be lowest when (z) in equation (1) is at a minimum. When the output y is constant, z will be minimized if the nutrient in the input used ($a'x$) is minimized. Therefore, the DEA model for defining the nutrient minimization is as follows (equation (4)):

$$\begin{aligned} & Min_{\lambda,x_i^{EE}} a_i' x_i^{EE} \\ \text{Subject to} \quad & -y_i + Y\lambda \geq 0, \\ & x_i^{EE} - X\lambda \geq 0, \\ & \textstyle\sum_{i=1}^{N} \lambda_i = 1 \\ & \lambda \geq 0 \end{aligned} \tag{4}$$

The above equation for pollution minimization is actually defined in the same manner as the cost minimization (in equation (2)) using an input-oriented DEA model (Coelli et al., 2005), where $x_i^{EE}$is the nutrient minimizing vector of input quantity for the i-th farm. To minimize emissions, the nutrient content, a, in equation (4) is, therefore, treated in the same manner as the input price, w, in equation (2) when seeking the lowest cost.

Environmental efficiency (EE) is then defined as the ratio of minimum nutrient content ($a_i' x_i^{EE}$) over the observed nutrient content ($a_i' x_i$):

$$EE = a_i' x_i^{EE} / a_i' x_i \tag{5}$$

When x_i^{TE} is the input vector at which a farm is technically efficient, technical efficiency[2] (TE) is defined as:

$$TE = \frac{x_i^{TE}}{x_i} = \frac{w_i' x_i^{TE}}{w_i' x_i} = \frac{a_i' x_i^{TE}}{a_i' x_i} \tag{6}$$

From the equations (3), (5) and (6), the input orientated cost and environmental efficiency can be decomposed into technical efficiency and cost (environmental) allocative efficiency as follows:

$$CE = \frac{w_i' x_i^{CE}}{w_i' x_i} = \frac{w_i' x_i^{CE}}{w_i' x_i^{TE}} \times \frac{w_i' x_i^{TE}}{w_i' x_i} = CAE \times TE \tag{7}$$

$$EE = \frac{a_i' x_i^{EE}}{a_i' x_i} = \frac{a_i' x_i^{EE}}{a_i' x_i^{TE}} \times \frac{a_i' x_i^{TE}}{a_i' x_i} = EAE \times TE \tag{8}$$

where cost allocative (CAE) and environmental allocative efficiency (EAE) are derived as:

$$CAE = \frac{w_i' x_i^{CE}}{w_i' x_i^{TE}} \tag{9}$$

$$EAE = \frac{a_i' x_i^{EE}}{a_i' x_i^{TE}} \tag{10}$$

As a non-parametric approach, DEA does not take into account random error. Moreover, efficiency is measured relative to the production frontier which is obtained from finite samples (Simar and Wilson, 1998). These characteristics of DEA are claimed to result in biased estimators. However, as shown by Pascoe and Mardle (2003) and Simar and Wilson (1998, 2000), this can be corrected by using a smoothed bootstrap procedure. The rationale behind bootstrapping is to repeatedly simulate a true sampling distribution by mimicking the data generating process through resampling and applying the original estimator to each simulated sample (Simar and Wilson, 1998). This study, therefore, employs the data envelopment approach with the smoothed bootstrap procedure introduced by Simar and Wilson (1998) to estimate economic and environmental efficiency scores.

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[2] Technical efficiency is the ability of a DMU to produce a given set of outputs from a minimum input mix and available technology or the ability of a DMU to produce a maximum output from a given set of inputs. Technical efficiency is a component of economic and environmental efficiency.

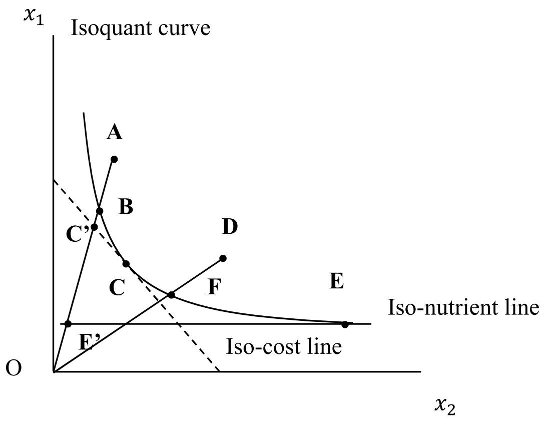

Fig. 1. The trade-off between cost and environmental efficiency.

2.4. Decomposition of and trade-off between cost and environmental efficiency

Given a nutrient-containing input x_1 and the input x_2 which does not contain nutrients, the graphical representation of the measurement of technical efficiency, cost and environmental allocative efficiency, and cost and environmental efficiency, using input orientated DEA, shows the intuitive interpretation of the above decomposition and the trade-offs between cost and environmental efficiency (Fig. 1).

In this figure, the technical efficient farms are those that lie on the isoquant curve. Hence, B, C, E and F are technically efficient farms. Meanwhile, A and D are technically inefficient farms. The technical efficiency (TE) of farm A is measured by the ratio:

$$TE = OB/OA$$

The cost efficiency (CE) of farm A is defined by the ratio:

$$CE = OC'/OA$$

Because the nutrient content in x_2 is zero, to minimize the total amount of nutrient release to the environment, farms can use x_2 as much as possible. The iso-nutrient curve, therefore, will be parallel with the horizontal axis. Any farm on this iso-nutrient line releases the same amount of nutrients to the environment. Hence, E and E′ are environmental allocative efficient points. However, the output of E' is lower than that at E, which is the intersection between iso-nutrient and isoquant. E is said to be technically efficient as well as environmentally allocative efficient. And the environmental efficiency (EE) of farm A can be estimated by the ratio:

$$EE = OE'/OA$$

The cost allocative (CAE) and environmental allocative efficiencies (EAE) of farm A can be calculated by using the above ratios:

$$CAE = \frac{CE}{TE} = \frac{OC'/OA}{OB/OA} = \frac{OC'}{OB}$$

$$EAE = \frac{EE}{TE} = \frac{OE'/OA}{OB/OA} = \frac{OE'}{OB}$$

The above decomposition implies that an increase in technical efficiency from A to B (or D to F) will result in an improvement in both the cost and environmental efficiency. The impact of cost allocative or environmental allocative efficiency on environmental and cost efficiencies, however, depends on where the farms are on the graph. For farm A, a movement from B to C to be cost efficient represents an increase in CAE. It also implies an improvement in environmental efficiency because this movement is on the way to reaching E to be environmentally efficient. This means that an increase in CAE will result in a rise in EE for farm A. On the contrary, an increase in CAE will lead to a fall in EE for farm D, because a movement from F to C to be cost efficient for this farm shows a greater distance from the environmentally efficient point (E). Based on such trade-offs, policy interventions can be suggested to improve environmental or economic performance by, for example, introducing taxes or removing subsidies on nutrient-containing inputs.

2.5. Data and variables

Data was collected from marine cage lobster farms in Khanh Hoa and Phu Yen provinces in Vietnam from August to November 2016. Those provinces were selected to be primary sampling units because they host more than 96% of the lobster cages in Vietnam (Minh et al., 2016; Petersen and Phuong, 2010). In total, 361 farmers were interviewed using a structured questionnaire, which was designed based on the results of expert interviews in July 2016. Looking at the production variables, using the outlier identification tool based on the data cloud method[3] available in the Benchmarking package in R, eight farms were found to be outliers and were removed from the sample (Bogetoft and Otto, 2011). Thus, a sample of 353 farms was used in this study. Based on the type of lobster cultivated, there are 150 ornate lobster farms, 166 scalloped lobster farms and 37 mixed cultivation farms. Mixed cultivation means that both types of lobster (ornate and scalloped lobster) are cultivated at the same farm, but in different cages. Because ornate and scalloped lobsters are different in terms of market size and production cycle, efficiencies for the three groups of farmers were measured based on three different frontiers.

Similar to other aquaculture production systems (Cinemre et al., 2006; Ferdous Alam, 2011; Ferdous Alam and Murshed-e-Jahan, 2008), this study takes productive services, materials and forces directly used in the lobster aquaculture production process as inputs (Curtis and Clonts, 1993). In this case these are feed, lobster seed and labor. These three inputs constitute between 92% (Petersen and Phuong, 2010) and 96% (Ton Nu Hai et al., 2018) of the total costs. Lobster production (measured in kilograms) is considered as output. The prices and nutrient content of these three inputs were used to measure cost efficiency and environmental efficiency in this study (Table 1). The descriptive statistics for the variables are shown in the Appendix. The information on these inputs and their prices was collected using a survey. For labor and seed,[4] the nutrient contents are assumed to be zero. The nutrient content in feed inputs is based on the study by Chien (2005). In this way, total nutrient in inputs is measured by multiplying the nutrient content with input quantities.

3. Results and discussion

3.1. Cost and environmental efficiency results

The cost and environmental efficiency scores for lobster farms are summarized in Table 2. The average cost efficiency scores for ornate lobster, scalloped lobster and mixed cultivation were respectively 0.564, 0.591 and 0.801. The mean environmental efficiency scores were only 0.392, 0.365, and 0.626. This implies that farms are not only cost inefficient but also substantially environmentally inefficient. On average, compared to the best practice, ornate lobster, scalloped lobster, and mixed cultivation farms should be able to produce their

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[3] The data cloud method is based on plotting the observations in a multidimensional space. The idea is that if we remove a firm from the data, the volume of the data cloud may change or not. If the removed farm is in the middle of the cloud, the volume will be unchanged but if that farm is far away from the other observations, the volume of the cloud will be reduced if it is taken out.

[4] The size of seed is so small (3 g on average) that nutrient content is negligible.

Table 1

Description of the variables in the DEA model (per farm per production cycle).

Variables	Description	Unit
Outputs	Total quantity of ornate (scalloped) lobster produced	Kilogram
Inputs		
Seed	Ornate (scalloped) seed cultivated	Unit
Feed	Quantity of trash fish for feeding lobster	Kilogram
Labor	Total working hours used for cultivating lobster	Man-hours
Price information for cost efficiency model		
Seed	The price of lobster seed	USD/unit
Feed	The price of feed	USD/kg
Labor	The price of labor	USD/man-hour
Nutrient content information for environmental efficiency model		
Seed	The proportion of nitrogen content in lobster seed	%
Feed	The proportion of nitrogen content in trash fish for feed	%
Labor	The proportion of nitrogen content in labor that is directly transformed to the lobster production	%

current output with an input bundle that, respectively, contains 60.8%, 63.5%, and 37.4% less nutrients. This result seems to be in line with the case of agricultural sectors in OECD countries (Hoang and Coelli, 2011), dairy farms in New Zealand (Ramilan et al., 2011), Korean rice farms in the study by Nguyen et al. (2012), and tomato farms in Almeria, Spain (Aldanondo-Ochoa et al., 2017). Such a reduction would mean that less pollution is released to the marine environment and thus less potential damage is caused.

Frequency distributions for the estimated efficiency scores are depicted in Fig. 2. The majority of the ornate lobster and scalloped lobster farms have a cost efficiency score between 0.6-0.8. The range of environmental efficiency scores was only 0.2–0.4 for the former, but 0.4–0.6 for the latter. Most of the mixed cultivation farms have a cost efficiency ranging from 0.8 to 1 and an environmental efficiency ranging from 0.6 to 0.8. This figure and the results in Table 6 also indicate that for the ornate lobster group, only 2% (3 out of 150 farms) were cost efficient and 3.3% (5 out of 150 farms) were environmentally efficient. For the scalloped lobster group, there were 5.4% (9 out of 166 farms) cost efficient farms and 3.6% (6 out of 166 farms) environmentally efficient farms. These numbers are much higher for the mixed cultivation group, with 24.3% (9 out of 37) and 18.9% (7 out of 37) respectively. The result for the mixed cultivation group could, however, be due to its much smaller sample size.

Overall, there seems to be great potential to simultaneously improve the environmental and economic performance of lobster farms in Vietnam. If farms improve their technical efficiency by reducing inputs, especially environmentally damaging inputs (i.e. trash fish used as feed), they could achieve both higher environmental efficiency and cost efficiency. This result was partially addressed by the study by Frank Asche et al. (2009) in the case of salmon aquaculture in Norway. It is furthermore in line with the results for other sectors by Thanh Nguyen et al. (2012) and Welch and Barnum (2009).

Fig. 3 compares environmental efficiency by subgroups (ornate lobster, scalloped lobster and mixed cultivation) of the 10% most cost efficient farms, the 10% most cost inefficient farms and the 10% of farms closest to the average cost efficiency.

In general, this figure shows the positive relationship between the environmental efficiency and cost efficiency score for all three groups. The more cost efficient farms are, the more environmentally efficient they are. However, for ornate lobster, there is only a small difference in environmental efficiency scores between the 10% most cost efficient farms (0.55) and the 10% farms closest to the average cost efficiency (0.54). The positive relationship between environmental efficiency and

Table 2

Cost and environmental efficiency scores using bootstrap DEA.

	Ornate lobster			Scalloped lobster			Mixed cultivation		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
TE	0.7564	0.4355	0.9186	0.6661	0.2679	0.9154	0.8961	0.6276	0.9472
CAE	0.7456	0.3985	1.0700	0.8906	0.4285	1.3200	0.8903	0.5814	1.0190
CE	0.5638	0.2435	0.8728	0.5912	0.2548	0.9206	0.8007	0.3649	0.9520
EAE	0.5044	0.1280	1.0374	0.5313	0.2367	1.0130	0.6814	0.3020	1.0180
EE	0.3926	0.0871	0.8801	0.3654	0.0897	0.7382	0.6259	0.2586	0.9540

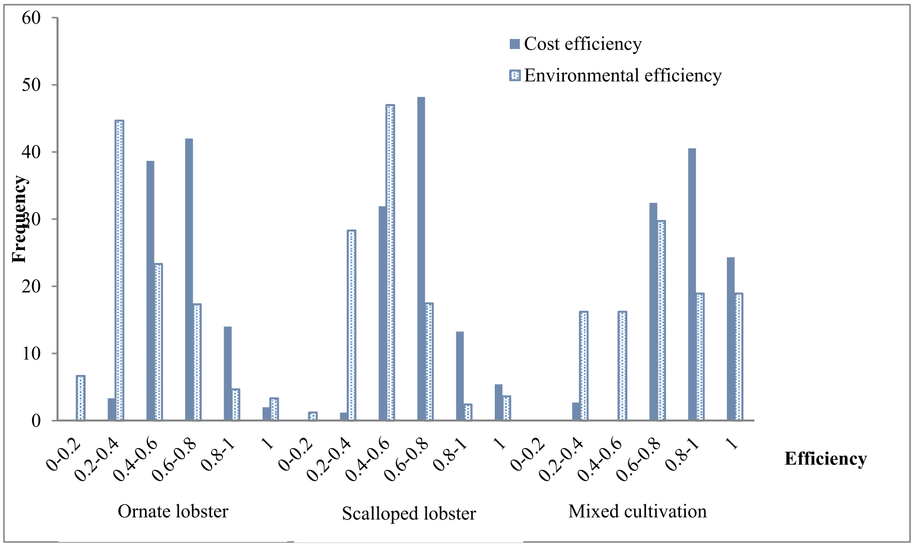

Fig. 2. Frequency distribution of cost and environmental efficiency.

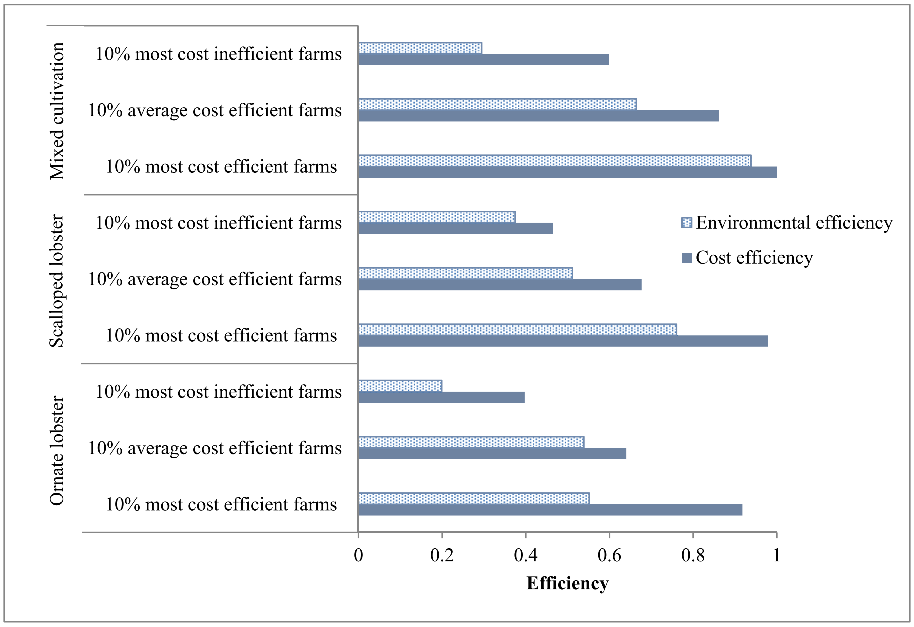

Fig. 3. Comparison of environmental efficiency among farms with average cost efficiency.

cost efficiency is further confirmed by the correlation coefficients and Spearman's rank test for the correlation between the efficiency measures presented in Table 3.

The results also show that 88.7% of the ornate lobster, 94% of scalloped lobster and 94.6% of mixed cultivation farms have cost efficiency levels greater than the environmental efficiency level. There were 2 out of 150 ornate lobster farms (1.3%), 5 out of 166 scalloped lobster farms (3%), and 5 out of 37 mixed cultivation farms (13.5%) achieving both cost and environmental efficiency. This suggests that most of the lobster production in the study area is targeted to minimize cost rather than environmental impact.

In addition, a comparison of some socio-demographic variables such as farm size (number of cages), frequency of cage cleaning during the production cycle (times), distance from the farm to the coast (km), and their spatial location for the 10% most efficient farms and the 10% least efficient farms by subgroups (ornate lobster, scalloped lobster and mixed cultivation) is presented in Table 4. The results show that the most inefficient farms for the scalloped lobster and mixed cultivation groups are mostly found in Vinh Hoa, Xuan Thinh commune, Song Cau town and Vung Ro, Hoa Xuan Nam commune, Dong Hoa district, Phu Yen province respectively. For the ornate lobster group, the most cost inefficient farms are found in Dam Mon, Van Ninh district while the most environmentally inefficient farms are more often located in 5A, Cam Phuc Nam commune, Cam Ranh district, Khanh Hoa province. Ornate lobster farms and scalloped lobster farms located close to the coast seem to be less efficient than those located further. The least cost and environmentally efficient scalloped lobster farms seem to clean their cages less frequently while the most cost efficient ornate lobster farms clean their cages more frequently. Cost and environmentally inefficient ornate lobster farms and environmentally inefficient scalloped lobster farms seem to be characterized by small farm sizes. For the cost efficiency of mixed cultivation farms, we observe an opposite trend.

3.2. Trade-offs between cost and environmental efficiency

Table 5 reports the relative changes in production cost and nutrient use of farms for four scenarios (1) a move from the current operation to a cost efficient operation, (2) a move from the current to an environmentally efficient operation, (3) the move from a cost efficient to an environmentally efficient position, and (4) the move from an environmentally efficient to a cost efficient position. Table 6 considers the same four scenarios and reports the number of farms having positive or negative trade-offs for these moves (see Table 6).

A positive trade-off implies that economic and environmental performance improves simultaneously, while a negative trade-off implies that as economic performances improves, environmental performance diminishes and vice-versa. Therefore, if the change in costs and the change in nutrient use have the same sign (both are negative or positive), there is a positive trade-off. On the contrary, if the change in costs and the change in nutrient use have an opposite sign, there is a negative economic-environmental trade-off.

The results in Tables 5 and 6 show a major trend of positive trade-offs in lobster aquaculture in Vietnam for the first two scenarios. For most farms, for all three cultivation types, the movement from the current position to both a cost efficient position and an environmentally efficient position is associated with reductions in both production cost and release of nutrients. For example, under scenario 1, 141 of the 150 ornate lobster farms (Table 6) have a negative value for both the change in costs and the change in nutrient use. Costs are, on average, 35.9% lower and nutrient use 49.6% (Table 5). This implies that most ornate lobster farms have a positive economic-environmental trade-off for moving from the current position to the cost-efficient point.

Table 3
Spearman correlation between efficiency measures.

	EE for ornate lobster	EE for scalloped lobster	EE for mixed cultivation
CE for ornate lobster	0.6511443***		
CE for scalloped lobster		0.6932192***	
CE for mixed cultivation			0.8281178***

*** Indicates significance at 1% levels.

Table 4
Comparison of some socio-demographic variables for the 10% most efficient farms and the 10% least efficient farms.

		Cost efficiency		Environmental efficiency	
		10% most efficient farms	10% least efficient farms	10% most efficient farms	10% least efficient farms
Ornate lobster	Farm size (No. cage)	21.20	13.73*	23.87	9.87**
	Cage cleaning frequency (times)	72.00	57.33*	95.47	52.53
	Distance to the coast (km)	4.60	1.96*	6.83	1.37***
	Primary location (% farms)	Dam Mon (27%)	Dam Mon (67%)	Van Thang (53%)	5A (67%)
Scalloped lobster	Farm size (No. cage)	16.94	14.47	22.69	9.53**
	Cage cleaning frequency (times)	179.29	276.71***	136.25	244.94***
	Distance to the coast (km)	1.21	0.30***	1.03	0.68
	Primary location (% farms)	Vinh Hoa (47%)	Vinh Hoa (88%)	Vinh Hoa (38%)	Vinh Hoa (59%)
Mixed cultivation	Farm size (No. cage)	12.00	22.75**	22.86	16.50
	Cage cleaning frequency (times)	93.00	126.00	120.00	156.00
	Distance to the coast (km)	1.48	1.2	1.32	1.05
	Primary location (% farms)	Vung Ro (50%)	Vung Ro (50%)	Vung Ro & Vinh Hoa (29% & 29%)	Vung Ro (75%)

*, **, and *** indicates significance at 10%, 5% and 1% levels.

These results, to some extent, seem to be in line with other studies focusing on this type of trade-off (Aldanondo-Ochoa et al., 2017; Doole and Kingwell, 2015; Lauwers, 2009; Thanh Nguyen et al., 2012; Van Meensel et al., 2010a, 2010b; Welch and Barnum, 2009). For example, Lauwers (2009) and Van Meensel et al. (2010a, 2010b) found a positive environmental economic trade-off for half of their sample of pig producing farms and Welch and Barnum (2009) indicated that some technically efficient electricity plants in the United States can simultaneously lower their costs and pollution levels by moving to the cost-efficient point on the isoquant. Likewise, in the study by Aldanondo Ochoa et al. (2017) most tomato farms in Almeria, Spain could move to the optimal cost position by improving environmental performance and some could reduce production costs by moving to the environmental optimum. Also, Thanh Nguyen et al. (2012) found a reduction in both the production cost and emissions when rice farms in Korea moved from the current position to full cost efficiency. However, in contrast to what we find, in their study, a movement from the current position to the environmental efficient point was found to be associated with an increase in production costs (Thanh Nguyen et al., 2012). This might be because the rice farms in the study by Thanh Nguyen et al. (2012) were producing within area D of Fig. 1, while most lobster farms in this study are situated in area A (Fig. 1).

In detail, on average, the movement of ornate lobster, scalloped lobster, and mixed cultivation farms from the current to the cost efficient position would not only reduce production costs by 35.9%, 32.1%, and 14.1% (equivalent to 12,415 USD, 5,729.9 USD, and 4,608 USD respectively) but also reduce nutrient consumption by 49.6%, 27.3%, and 17.1% respectively (equivalent to 107.1 kg, 56.6 kg, and 60.2 kg per farm for ornate lobster, scalloped lobster and mixed cultivation farms respectively) without changing the output produced. Equivalently, if the ornate lobster, scalloped lobster, and mixed cultivation groups were to move from the current position to an environmentally efficient position, they would not only reduce nutrient consumption by 55.3%, 49% and 30% (equivalent to 113.9 kg, 81.7 kg, and 93.7 kg of nutrient respectively) but also reduce production costs by around 19.5%, 21.8%, and 1.4% (equivalent to 6,743 USD, 3,891.3 USD, and 457.6 USD respectively).

However, the movement of most lobster farms from the cost efficient to the environmentally efficient position, or vice-versa, is associated with negative trade-offs. This implies that for farms that were using the optimal combination in terms of nutrient content of inputs, producing at a lower cost combination of inputs could reduce their production costs, but would lead to a cost to the marine environment due to the increased pollution power of these input combinations. Similarly, for most of the farms that were using the least cost combination of inputs, producing with less polluting combinations of inputs could improve their environmental efficiency, but this leads to additional production costs.

This illustrates that there is a substantial gap between the iso-quant–iso-nutrient and the iso-quant–iso-cost tangent points, which means that any technically-efficient farm that exists at or between one of these points can only reduce nutrient release by increasing costs, or only reduce costs by increasing nutrient release. In detail, if ornate lobster, scalloped lobster and mixed cultivation farms were to move from a cost efficient to an environmentally efficient position, the production cost would increase by 26%, 16.4%, and 16.2%, while the nutrient use would decrease by 9%, 28.3%, and 16.5% respectively. Similarly, if they were to move from the environmentally efficient

Table 5
The relative change (%) in production cost and nutrient consumption for being cost and environmentally efficient.

		Ornate lobster		Scalloped lobster		Mixed cultivation	
		Cost change	Nutrient change	Cost change	Nutrient change	Cost change	Nutrient change
(1) From the current to CE	Mean	-35.9	-49.6	-32.1	-27.3	-14.1	-17.1
	Min	-70.6	-89.2	-71.8	-80.7	-60.9	-61.5
	Max	0	85.9	0	40.6	0	113.9
(2) From the current to EE	Mean	-19.5	-55.3	-21.8	-49.0	-1.4	-30.7
	Min	-58.5	-89.6	-70.0	-89.4	-53.1	-78.0
	Max	69.9	0	41.7	0	43.2	0
(3) From CE to EE	Mean	26.0	-9.0	16.4	-28.3	16.2	-16.5
	Min	0	-49.7	0	-59.0	0	-53.2
	Max	106.5	0	51.0	0	56.9	0
(4) From EE to CE	Mean	-18.4	12.7	-13.0	46.8	-12.6	24.4
	Min	-51.6	0	-33.8	0	-36.3	0
	Max	0	98.8	0	144.2	0	113.9

Table 6

Number of farms that have positive/negative cost-environmental trade-off.

		Ornate lobster		Scalloped lobster		Mixed cultivation	
		Cost Change	Nutrient Change	Cost Change	Nutrient change	Cost Change	Nutrient change
(1) From the current to CE	(-)	147	141	157	135	28	24
	(0)	3	3	9	9	9	9
	(+)	0	6	0	22	0	4
(2) From the current to EE	(-)	115	145	150	160	16	30
	(0)	5	5	6	6	7	7
	(+)	30	0	10	0	14	0
(3) From CE to EE	(-)	0	148	0	154	0	32
	(0)	2	2	12	12	5	5
	(+)	148	0	154	0	32	0
(4) From EE to CE	(-)	148	0	154	0	32	0
	(0)	2	2	12	12	5	5
	(+)	0	148	0	154	0	32

position to the cost efficient position, costs would be reduced by 18.4%, 13%, and 12.6%, but nutrient use would increase by 12.7%, 46.8% and 24.4%. The studies by Welch and Barnum (2009) and Thanh Nguyen et al. (2012) also found a similar negative environmental economic trade-off in terms of both movement from the cost efficient position to the environmentally efficient position and vice versa.

4. Conclusion

While the aquaculture sector has grown significantly over recent years, concerns about its environmental impacts are also growing (Henriksson et al., 2017; Ottinger et al., 2016). This is also the case for marine cage lobster aquaculture in Vietnam. Using a Material balance Principle (MBP) based Data Envelopment Analysis (DEA) approach, the trade-offs between economic and environmental efficiency for cage lobster farming in Vietnam were explored. When cage lobster farms move from the current to a cost efficient position, this reduces both production costs and nutrient release. When farms move from the current to an environmentally efficient position, the changes in nutrient consumption were −55.3%, −49.0% and −30.7%; and those for production costs were −19.5%, −21.8%, and −1.4% respectively.

These findings show that efficiency improvements in input use would result in better environmental performance and lower production costs. Starting from the current production situation, most lobster farms would establish positive economic-environmental trade-offs when moving towards environmentally efficient or cost efficient positions. If lobster farms used the appropriate input mix, given input price information, to become more cost efficient, this would also benefit the environment. Equivalently, producing in a more environmentally friendly way would also reduce production costs. However, for all three groups, there is a substantial gap between the cost efficient and environmentally efficient production point, causing a negative trade-off for the move from the cost efficient to the environmentally efficient position and from the environmentally efficient to the cost efficient position.

The results indicate that technical training programs on how to use inputs efficiently and/or choosing better input combinations, given input price information, can significantly improve both the economic and environmental efficiency of lobster aquaculture. Such technical training programs should be especially given to farm with small size and located close to the coast in the location of Dam Mon, Van Ninh district and 5A, Cam Ranh district, Khanh Hoa province for ornate lobster group and Vinh Hoa, Song Cau town, Phu Yen province for scalloped lobster group but with large farm size in Vung Ro, Dong Hoa district, Phu Yen province for mixed cultivation group. Moreover, farmers from scalloped lobster group should be informed to reduce the input used (especially feed) to be more efficient rather than investing in cleaning their cages to reduce pollution impacts. Overall, our findings clearly show that there is a significant opportunity for the application of the DEA–MBP method to help inform marine aquaculture development. It seems reasonable to consider new incentive systems to encourage the selection of other production technologies or operational techniques that would simultaneously comply with the desire for cost efficiency and the need to reduce nitrogen emissions. Input taxes (especially feed taxes) and/or emission taxes could be applied to obtain a positive economic-environmental trade-off. Applying such taxes would stimulate farmers to use input combinations containing less nutrients. This solution could also stimulate farmers to improve technical efficiency by using lower nutrient inputs to produce the same amount of output, or to produce more output without changing inputs. At the other hand, output price taxes might also be a useful tool to obtain this win-win relationship. A decrease in output price by applying an output price tax could steer farmers to reduce their output and thereby to reduce the inputs use including feed.

While the current paper only takes into account one pollutant, which for this study case was considered to be the most important, it is well known that overuse of antibiotics and other chemicals (pesticides, fertilizers) in the aquaculture sector also causes water pollution (Ottinger et al., 2016). Moreover, this study only considers productive services, material, forces directly used in production process as inputs of the sector (Curtis and Clonts, 1993) these include feed, seed, and labour. Results might change if other inputs are added in the DEA model. Future research could for instance look at the effect of considering the cages as inputs.

Declaration of competing interest

There is no conflict of interest.

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Appendix

Table A
Descriptive statistics for variables included in DEA model (per farm per production cycle).

	Ornate lobster			Scalloped lobster			Mixed cultivation		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Outputs									
Ornate	136	736.7	2,240	0	0	0	90	757.3	2,400
Scalloped	0	0	0	72	783.9	3,600	135	774.7	2,400
Inputs									
Feed	1,590	13,605	50,010	684	12,440	57,586	2,547	22,643	105,323
Labor	420	3,355	10,320	480	2,009	7,920	1,620	3,466	6,480
Seed									
Ornate	150	1,028	2,800	na	na	na	100	977	2,670
Scalloped	na	na	na	240	2,793	12,000	600	3,067	11,200
Price information for cost efficiency model									
Feed	0.46	1.30	2.65	0.34	0.62	1.53	0.24	0.59	1.02
Labor	0.48	0.73	1.51	0.53	1.23	2.20	1.06	1.24	3.85
Seed									
Ornate	3.30	14.54	24.23	na	na	na	3.52	10.46	26.43
Scalloped	na	na	na	1.50	2.90	4.41	1.06	2.60	4.41
Nutrient content information for environmental efficiency model									
Feed	-	1.337	-	-	1.337	-	-	1.337	-
Labor	-	0	-	-	0	-	-	0	-
Seed	-	0	-	-	0	-	-	0	-

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