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Is economies of scale driving the development in shrimp farming from Penaeus monodon to Litopenaeus vannamei? The case of Indonesia

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ABSTRACT

Globally shrimp farming have grown substantially over the last 2 decades. The growth in farmed shrimp is driven by increasing worldwide demand due to population and income growth, while wild supply is stagnating. The growth mainly seems to appear within the species Litopenaeus vannamei, while Penaeus monodon production is stagnating. The development in Indonesia mirrors the global development, were L. vannamei has surpassed the volume of P. monodon several times in 2020. Interviews with 96 L. vannamei and 87 P. monodon farmers are conducted to collect farm level economic data. Using data envelopment analysis, technical efficiency is estimated and production possibility frontiers are compared. Furthermore, a new permutation test is used for identifying returns to scale characteristics, and increasing returns to scale is identified. The production possibility frontiers are found significantly different for the two species without one being nested inside the other. For large farms with high production volume, L. vannamei is superior, whereas P. monodon has the advantages in smaller farms. Hence, one farm size does not fit all. The implication is that L. vannamei farms can take advantage of economies of scale and expand, while small P. monodon farms coexist by supplying larger shrimp to an international high-quality markets.

1. Introduction

On a global scale, farming of shrimp have been increasing over the past two decades, while wild catches have been stagnating. The growing production is mainly due to increasing demand driven by population and income growth, and a rising preference for healthy food. The leading species in this development have been Litopenaeus vannamei. The global production of L. vannamei has increased from 155 thousand tonne in 2000 to 5.8 million tonne in 2020. On the other hand, the previously leading species, Penaeus monodon, has not experienced the same growth and remains on a rather constant level with a production only increasing from 631 thousand tonne in 2000 to 717 thousand tonne in 2020 (FAO, 2022). Thus, Indonesia is used as a case study, since it mirrors the development within these two shrimp species worldwide.

The continued expansion of L. vannamei production and the stagnating production of P. monodon raises some interesting production economic questions and the need for further analysis of the production economic characteristics of the two species. In Indonesia, the continuous growth of L. vannamei seems to be correlated with the development of larger farms in terms of size and production volume, indicate that increasing returns to scale may exist. At the same time, the survival of P. monodon production in smaller traditional farms points toward some economic advantages compared to L. vannamei at this farm size and production level.

The purpose of this paper is to analyze the role of economies of scale for the development of the production of the two species L. vannamei and P. monodon in Indonesia. Economies of scale is analyzed along two directions. First, technical efficiency is estimated using data envelopment analysis (DEA) and efficiency scores applied to test for increasing returns to scale separately in farming of L. vannamei and P. monodon using a newly developed permutation test (Ramm-Nielsen et al., 2022). Second, given the identified returns to scale assumption, production possibility

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frontiers are compared for the two species to reveal whether one is nested inside the other, i.e. generally worse, or whether one is perhaps only better than the other for particular farm sizes in terms of production volume.

The implication of the possible presence of increasing returns to scale in L. vannamei farming is that investments may remain advantageous in this species with the continued option of taking advantage of economies of scale. Investment can be made both in extensions of existing farms and in construction of new large farms. These farms target the market with large quantities of shrimp at a small to medium size (1.39–10.9 g/piece) (Samadan, 2018). Simultaneously, the implication of the possible superiority of P. monodon for small farms is that investments may remain advantageous also in this species, but on small farms specialized in the production of mainly large shrimp (17.7–20.1 g/piece) (Sann et al., 2000). These farms target an international high-quality market for large-sized shrimp, as reflected by the average export price of P. monodon being 40% higher than that for L. vannamei in 2020 (11.49 US$/kg and 8.23 US$/kg, respectively) (DGofPC, 2021). While the largest P. monodon shrimp can be sold with a price premium, smaller sized P. monodon are also produced (Arnold et al., 2009; Wade et al., 2015). These medium sized shrimp are sold in the same market as L. vannamei. The specialization in different shrimp species with different sizes may also indicate that different farm technologies (species) and sizes offer different economic advantages and therefore are able to coexist.

Shrimp are studied in three directions of relevance for the evolution in Indonesia. Market studies indicate that prices of shrimp are formed at internationally integrated markets where prices move together over time for different species, different sizes, whether farmed or wild-caught and in different countries (Vinuya, 2007; Nielsen et al., 2009; Asche et al., 2012; Ankamah-Yeboah et al., 2017; Hossain et al., 2021). While markets are integrated, price premiums are identified for large-sized shrimp as reflected by the price premium of large warm-water shrimp over small cold-water shrimp (Ankamah-Yeboah et al., 2017; Hukom et al., 2020a).

A second direction study technical efficiency in shrimp farming using DEA and stochastic frontier analysis (SFA). Shang et al. (1998) analyzed economic efficiency of extensive, semi-intensive and intensive shrimp farming in several Asian countries and the lowest production costs were found in extensive systems, followed by semi-intensive and intensive systems. A noticeable exception was in India, where the production costs was highest in the semi-intensive system. Nguyen (2012) analyzed technical efficiency assuming variable returns to scale for P. monodon and L. vannamei. The results showed that technical efficiency was highest for P. monodon. Hukom et al. (2020b) identified a positive correlation between good water quality and technical efficiency for farmers of L. vannamei in Indonesia. Finally, Hukom et al. (2022) investigated the effects of co-management on technical efficiency using DEA and found technical efficiency was higher in areas where co-management is applied.

A third direction follows from the studies of technical efficiency, but focus on economies of scale in shrimp farming. Kumar and Birlhal (2004) found large shrimp farms more efficient than small shrimp farms. Long et al. (2020a) and Long et al. (2020b) also found that intensive L. vannamei farms in Vietnam improved efficiency when becoming larger and having access to credit, while Nguyen and Fisher (2014) found the opposite, i.e. that extensive shrimp production is more efficient. More studies used SFA to identify correlation between technical efficiency on one hand and duration of culture and technology adoption, education of farmers, stocking density and feed quality on the other (Begum et al., 2013; Begum et al., 2016; Kumar et al., 2017; Reddy et al., 2008).

This paper builds upon existing literature by combining tests of increasing returns to scale with comparison of production possibility frontiers to analyze the market-induced performance differences between production technology (shrimp species) and farms size. Thereby, new knowledge is obtained on the best practice industry structure for L. vannamei and P. monodon.

### 1.1. Case study

Shrimp aquaculture production in Indonesia is dominated by two species P. monodon and L. vannamei. Since the mid-1970s, P. monodon has been cultured in Indonesia. The production was further developed in the 1980s (Yi et al., 2018) and has been the main shrimp species produced in Indonesia since 1990. However, there has been a decline in production from 1997 to 2000 due to diseases, which was a worldwide phenomenon (Lee et al., 2022). During this period, many farmers looked for alternative species and started to switch species to L. vannamei, a shrimp species from the west coast of Latin America (Briggs et al., 2004). The development of the production of the two species in Indonesia is presented in Fig. 1. The figure show a relative constant production of P. monodon, whereas L. vannamei experienced a tremendous growth from 2004 until 2017, followed by a small dip in the production volume until 2020.

The global production of the two species is presented in Fig. 2, and the global production trend mirrors the Indonesian development. The production of P. monodon was slightly increasing from 1990 to 2020. On the other hand, L. vannamei production started to increase from around 2000 and surpassed P. monodon already in 2003 and reached a production volume seven times higher than P. monodon in 2020.

While production of P. monodon is stagnating, farmers still choose to continue to culture P. monodon. One of the reasons for this is that it has a higher selling price than L. vannamei. The lowest selling price of P. monodon is 3.6 USD per kilogram, while the highest is 9.2 USD per kilogram. Meanwhile, the lowest selling price of L. vannamei is 3.8 USD per kilogram, and the highest price reached 6.8 USD per kilogram. Furthermore, P. monodon’s average weight for harvest is up to 28 g per head, while L. vannamei is 19 g per head (Sookying and Davis, 2011; Sahu et al., 2013). Finally, the growth rate of P. monodon is higher than L. vannamei, with an average of 0.17 g per day (Liao and Chien, 2011).

P. monodon is an indigenous species whose cultivation seems efficient if carried out on a micro-scale, often cultivated in polyculture with various other fish species (Martínez-Porchas et al., 2010; Fitzsimmons and Shahkar, 2017; Anh et al., 2020). In contrast, L. vannamei production seems to benefit from being cultivated on a larger scale (Yi et al., 2018; Nisar et al., 2021), which requires relatively large investments (Ponce-Palafoux et al., 2011) and therefore it is more suitable for monoculture systems with intensive handling.

The preference for producing L. vannamei stems from the fact that the production and income levels for L. vannamei ponds are higher than for P. monodon (Nisar et al., 2021). Furthermore, the risk when cultivating P. monodon is greater than that of L. vannamei (Nisar et al., 2021) for the following three reasons:

First, P. monodon has a lower survival rate (51% - 68%) than L. vannamei (83%) on average. This is because L. vannamei seeds can be obtained from successfully domesticated broodstocks and can be produced pathogen free (SPF - Specific Pathogen Free), while P. monodon is still harvested from nature. Thus, the availability of L. vannamei seeds is higher than P. monodon. Furthermore, L. vannamei have a low rate of cannibalism, making it easier for farmers in the cultivation process (Wyban, 2007).

Secondly, P. monodon has a higher feed conversion ratio (1.3–1.5), which means that to produce 1 kg of shrimp 1.3–1.5 kg feed is needed (Arifin et al., 2018). This is relatively high compared to L. vannamei (1.11–1.23 kg) (Esparrza-Leal et al., 2010; Shaker et al., 2014; Supono., 2021). L. vannamei is responsive to feed with around 30% protein content (Liao and Liu, 1989; Supono., 2021), which is lower than for P. monodon with a range of 35–45% protein content (Liao and Liu, 1989).

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Finally, *L. vannamei* can be managed with high seed stocking densities and still have a higher survival rate (83%) than *P. monodon* (54%) (Supono., 2021). This also makes the productivity per hectare of *L. vannamei* higher than for *P. monodon*. Thus, *L. vannamei* can reach a production of 15,000 kg per hectare, while *P. monodon* can only reach a production of 6,300 kg per hectare (Supono., 2021).

### 2. Material and method

#### 2.1. Field data collection

For the present study, data was collected in Sidoarjo, one of the top-producing shrimp districts in Indonesia, located in East Java Province (Fig. 3 left diagram). Eight coastal sub-districts are producing shrimps, from Waru to Jabon (Fig. 3 right diagram). Sidoarjo is an optimal place for both *P. monodon* and *L. vannamei* to grow because of its favorable environmental characteristics, with temperatures ranging from 20 °C to 35 °C. Farmers in Sidoarjo have produced shrimps for more than one hundred years. In this district, many farmers have shifted to *L. vannamei*, however some still cultivate *P. monodon*.

Interviews were conducted with 96 *L. vannamei* farmers and 87 *P. monodon* farmers, from October 2017 to June 2018. The data collected include inputs for production such as seed, feed, labor and other costs (including lime, medicine and gas).

In Table 1, the average size in hectare, the output yield in weight (kg) and value (USD) and input costs are shown for the two species investigated. In general both farm size, output yield and costs are higher for *L. vannamei* farmers. For *L. vannamei*, the seed cost are higher than *P. monodon* due to the higher stocking density in *L. vannamei* farms. Feed cost include pellets used for feeding. Labor costs include wages for laborers who work during pond preparation, operation, and harvest. Other costs represent on average 10% for *L. vannamei* and 7% for *P. monodon* and include lime and medicine to prevent and treat disease, and gasoline used for pumping water in and out of farms.

In Fig. 4, the average running cost component structure for the four inputs used are shown for the two species. Feed, labor, and seed are the most important inputs for *L. vannamei*’s production, respectively. For *P. monodon* farmers, the highest running cost shares are used for labor, seed, and feed, respectively, with a relative lower amount spend on other cost items.

Comparing the two running cost component structures may reveal that the *L. vannamei* producers have reached a higher degree of maturity than *P. monodon* producers. This follows the argument that aquaculture industries over time will be able to reduce most cost items due to increased productivity and technological development, however, feed remains a central input in converting protein to shrimps and will have a relative higher cost share when the industry matures, as has, for example, been seen in the Norwegian salmon aquaculture industry (Guttormsen, 2002). On the other hand, *P. monodon* farmers use relatively more labor, which may indicate that this production can be characterized as subsistence farming, where the polyculture system provides food for the local community and only the shrimp produced are sold to foreign markets to provide an extra income (Lahiri et al., 2022).

#### 2.2. Data envelopment analysis

Like many previous studies, we use Data Envelopment Analysis (DEA) (c.f. Charnes et al., 1978) to analyze the efficiency of shrimp
farms (see e.g. Hukom et al. (2020b), Hukom et al. (2022), Long et al. (2020a), Long et al. (2020b), Nguyen and Fisher (2014), Kumar and Birthal (2004), Shang et al. (1998)). Some of the advantages of DEA are that it can simultaneously consider multiple inputs and multiple outputs, and does not require a specification of the functional form of the relationship between inputs and outputs, nor of the distribution of the (in)efficiency scores. Furthermore, we are here specifically interested in analysing which of two production technologies (here species of shrimp) offers better production possibilities for each farm, and this is more easily investigated using DEA than using e.g. Stochastic Frontier Analysis.

Whilst DEA relies on very few assumptions, it is, nevertheless, necessary to make an assumption about the returns to scale characteristics of the underlying production technology. However, recent methodological developments makes it possible to statistically test whether another returns to scale assumption describes the input-output relationship in the observed data set better than the constant returns to scale assumption (Rønn-Nielsen et al., 2022). As the literature largely argues for economies of scale in shrimp production, we specifically test the assumption of increasing returns to scale (IRS)\(^2\) against the baseline assumption of constant returns to scale (CRS). In this paper, we apply these recently developed tests to examine the appropriate returns to scale assumption for the set of shrimp farms in Indonesia. Since the analysis concerns two distinct production technologies (species) it is important to estimate the production possibilities for these two technologies separately, as they may have different properties and, furthermore, it is not appropriate to estimate a technology based on convex combination of farms of different types, as those will not constitute appropriate or realistic benchmarks.

For the DEA analysis, consider a data set comprising \(k=1, \ldots, K\) and \(j=1, \ldots, n\) observations from each of the two production technologies, specifically the farming of \(L.\ vannamei\) and \(P.\ monodon\) respectively. The observations (farms) from either technology use \(m\) different inputs (\(i=1, \ldots, m\)) to produce \(n\) different outputs, (\(j=1, \ldots, n\)). Farm \(k\) is defined by its input vector \(x^k = (x^k_1, \ldots, x^k_m) \in \mathbb{R}^m\) and its output vector \(y^k = (y^k_1, \ldots, y^k_n) \in \mathbb{R}^n\), where \(x^k_i > 0\) is the consumed quantity of the \(i\)th input for \(DMU\) \(k\) and \(y^k_j > 0\) is the produced quantity of the \(j\)th output for \(DMU\) \(k\) (and similarly for a farm \(k\)).

In the present analysis there are 96 \(L.\ vannamei\) farmers, 87 \(P.\ monodon\) farmers and we estimate their production technologies considering 4 inputs and 1 output. Therefore, \(K = 96, K^c = 87, m = 4\) and \(n = 1\).

The input-oriented efficiency score for a given farm \(k^0\) belonging to the \(L.\ vannamei\) technology (and similarly for a farm belonging to the \(P.\ monodon\) technology) can, under the assumption of constant returns to scale, be estimated using the following linear programming (LP) problem:

\[
\begin{align*}
\phi^0_{\text{CRS}} &= \text{Min } \theta \\
\sum_{i=1}^{m} x^i &\leq \theta x^i_i, i = 1, \ldots, m \\
\sum_{i=1}^{m} \theta y^i &\geq y^0_i, j = 1, \ldots, n \\
\theta &\geq 0, k = 1, \ldots, K.
\end{align*}
\]

If variable returns to scale (VRS) is assumed instead of CRS, then the

\[\text{Strictly speaking, the assumption is about non-decreasing returns to scale, but the more intuitive term of increasing returns to scale is often used instead.}\]
corresponding efficiency score \( e_{\text{VRS}} \) can be estimated by adding an additional constraint \( \sum_{k=1}^{K} x_k^i = 1 \), to the LP problem (1) and if IRS is assumed, then the efficiency score \( e_{\text{IRS}} \) can be estimated by instead adding the constraint \( \sum_{k=1}^{K} x_k^i \geq 1 \) to problem (1).

A measure of scale efficiency can, for a given farm \( k^0 \), be estimated as the ratio of the efficiency score under CRS to the efficiency score under VRS, i.e.

\[
SE^0 = \frac{e_{\text{VRS}}}{e_{\text{CRS}}}.
\]

A scale efficiency (SE) score of 1 indicates that the given farm is operating on the most productive scale size (within the given species), and the smaller the score, the further the scale of operation is away from the optimal.

To formally test whether IRS significantly better describes the production technology than CRS, we apply the permutation test for returns to scale of Rønn-Nielsen et al. (2022), modified for the case of IRS. After a conclusion has been reached on the appropriate returns to scale assumption, we can compare the estimated frontiers for the two technologies in order to determine which production technology (species) offers the best production possibilities. Rønn-Nielsen et al. (2022) also offers significance tests for whether two frontiers are significantly different or not, and an additional test for whether different frontiers are in fact nested within each other’s (as opposed to intersecting). In the following, we apply both these tests, modified to the case of IRS.

Fig. 5 below illustrates, in a simplified case of 1 input - 1 output technologies with IRS, the presence of nested frontiers (left panel) and of different and intersecting (but not nested) frontiers (right panel).

In the left panel of Fig. 5, we see that the blue frontier, and thus the production possibility set for the blue producers is nested within the production possibility set for the red producers (i.e. the blue technology is a subset of the red technology). This means that the red producers have better production possibilities regardless of their size, since there are input-output combinations that are possible for the red producers which are not possible for the blue producers, in particular combinations using less input for a given level of output. In the right panel, the production possibility sets are different, but without one being nested within, and thus consistently better than, the other, since the frontiers intersect. Specifically we see that for small producers (with output levels below around 7.5 (on this arbitrary scale in the illustration in Fig. 5)) does the blue technology offer better production possibilities than the red technology, since the blue frontier is here located “to the left” of the red frontier. This indicates that it is possible to produce output using less input in the blue technology than in the red technology for output levels up to 7.5. For the larger producers (with output over 7.5) however, it is the other way around, with the red technology being located to the left of the blue technology and thus offering better production possibilities (specifically lower input use given the output level). Thus whilst the estimated frontiers are still different, they are here not nested (with one inside the other) but rather they intersect. The tests proposed in Rønn-Nielsen et al. (2022) makes it possible to determine whether any two frontiers are significantly different, and, if so, whether the frontiers are then nested, or different but intersecting.

A measure of the difference between the frontiers for the two production technologies for the \( P. monodon \) farmers and the \( L. vannamei \) farms respectively, for a given farm \( k^0 \), can be defined as

\[
FD^0 = \frac{e_{\text{IRS,MON}}}{e_{\text{IRS,VAN}}}.
\]

where the subscript “IRS_MON” indicates that the efficiency score is estimated relative to the frontier spanned by the \( P. monodon \) farms alone (and assuming IRS) and similarly for “IRS_VAN” and the \( L. vannamei \) farms. A frontier difference (FD) score larger than 1, means that the \( L. vannamei \) technology offers better production possibilities than the \( P. monodon \) technology for the farm under analysis (farm \( k^0 \)). Conversely, if \( FD^0 < 1 \) then the \( P. monodon \) technology is superior to the \( L. vannamei \) technology for farm \( k^0 \). An FD score larger than 1 means that, for a given farm, the efficiency score relative to the \( P. monodon \) technology is larger than the efficiency score relative to the \( L. vannamei \) technology, which, in turn, means that the frontier for the \( P. monodon \) producers is located closer to the given observation than the \( L. vannamei \) frontier, and therefore that the \( L. vannamei \) technology offers better production possibilities. If the red technology in Fig. 1 corresponds to \( L. vannamei \) and the blue technology to \( P. monodon \) then the left panel would yield FD scores all above 1, whereas the right panel would result in FD scores above 1 for the large producers and FD scores below for the small producers.

When comparing the technologies it is worth noting, that we do not, like many other studies (see e.g. Rahman et al., 2019) use the so-called meta-frontier approach, which constructs a common frontier based on all the farms, i.e. across both species. This is because this frontier will consist of points that are constructed as convex combinations of farms with different species. And since none of the farms actually produce both species of shrimp, it is not appropriate to use such artificial constructions (that implies production of both species) as benchmarks. Instead we in Eq. (3) directly compare the (differences between the) separately estimated frontiers for each of the species.

Finally, note that if the sample sizes of the groups being compared are (very) different, it is necessary to control for this using a jackknifing approach. Therefore, we have done 100 jackknife replications within each of the 1000 permutations performed within each significance test for frontier differences. In the present data set, there are 96 \( L. vannamei \) producers and 87 \( P. monodon \) producers, and since the sample sizes are quite similar, a large number of jackknife replications controlling for sample size differences is not really needed.
3. Results and discussion

3.1. Returns to scale

Since the overarching premise of the analyses is that the production possibilities for the L. vannamei and the P. monodon producers might be different, the frontiers and resulting efficiency scores are estimated within each species separately. Consider first the scale efficiency scores plotted against a measure of size (output quantity) within each species, as illustrated in Fig. 6.

It is clear from Fig. 6 that there is a positive relationship between size and scale efficiency within each species, since larger producers tend to
have higher scale efficiency scores than the smaller producers, and the lowest scale efficiency scores are found amongst the smallest producers (with one exception amongst the L. vannamei producers). Since larger scale efficiency scores (≤1) indicates that farms are operating closer to the optimal scale (or most productive scale size), the positive relationship between scale efficiency and size indicates the presence of increasing returns to scale (IRS) within each species. Furthermore, we observe that the scales of operations are quite different between the species, with the mean produced quantity being 2,506 kg for the P. monodon producers and 5,791 kg for the L. vannamei producers, and even bigger differences in terms of the total revenue, with the mean being 7,394 USD for the P. monodon producers and 23,695 USD for the L. vannamei producers (c.f. Table 1).

It can also be shown that of the 19 L. vannamei producers that are efficient under variable returns to scale (VRS), 11 are operating on the most productive scale size (exhibiting CRS), whereas 6 are operating under IRS and only 2 are operating under decreasing returns to scale (DRS). Similarly, out of the 29 VRS efficient P. monodon producers, 6 are operating on the most productive scale size, whereas 23 exhibit IRS and none show DRS. Thus, there are rarely disadvantages from being too big, but often potential advantages from increasing the scale of production within both species (though from very different starting points in terms of size of production). For details on returns to scale classifications in DEA please see e.g. Banker (1984).

We now move on to test whether the IRS estimation of the production technology is actually significantly different from the CRS estimation within each of the species. We therefore modify the permutation test of Rønn-Nielsen et al. (2022), to examine, within each species, whether a technology assuming IRS is significantly different from the CRS technology. The p-values from these tests with 1000 permutations is lower than \( p \leq 0.001 \) for both the P. monodon and the L. vannamei producers, which leads us to clearly reject the CRS assumption in favor of the IRS assumption. Thus, any subsequent analysis for either type of producers should be done using a model assuming IRS.

### 3.2. Comparing production possibilities between species

Modifying the permutation tests\(^3\) for frontier differences from Rønn-Nielsen et al. (2022) to the case of IRS, means that we can first determine whether the production possibilities for the P. monodon and the L. vannamei producers are similar or significantly different and next determine whether one frontier is, in fact, nested within the other.

The p-value from the first of these tests (≈0.02) tells us that the frontiers for the production possibilities for the P. monodon and the L. vannamei producers are significantly different. The p-value from the second of the tests (≈0.80) tells us that one is not nested inside the other. This means that we can conclude that the frontiers are different, but one is not clearly better than the other meaning that they intersect (corresponding to the illustration in the right panel in Fig. 1). Thus, for some of the farms, producing P. monodon provides better production possibilities than producing L. vannamei, whereas it for others is the other way around. This means that “one species does not fit all” and the best choice of production technology (species) will depend on other factors such as size, input mix etc., which we will look further into in the following.

With respect to size, we find a strongly significant positive correlation between the measure of whether and how much the L. vannamei technology is better than the P. monodon technology (the FD measure from Eq. (3), which if larger than one means that the L. vannamei technology is best, and the larger the value the more superior is the L. vannamei technology) and then the size of the farm, regardless of whether the latter is quantified by the output quantity and the total revenue. This means that the larger the farm, the more superior is the L. vannamei technology. Alternatively, we note that the producers for which the P. monodon technology is superior produces an average of 2,506 kg or 7,394 USD compared to 5,791 kg or 23,695 USD for those producers for which the L. vannamei technology is superior.

It can be noted that 56 out of the 87 P. monodon are, in fact, located in the part of the production space where the P. monodon technology provides superior production possibilities, and conversely that 71 out of the 96 L. vannamei producers are located where the L. vannamei technology is superior.

While increasing returns to scale in shrimp farming have been studied earlier (Kumar and BIRTHAL, 2004; Long et al., 2020a; Long et al., 2020b; Nguyen and Fisher (2014)), this paper is, to the knowledge of the authors, the first to show that the P. monodon technology is superior on smaller farms, while simultaneously the L. vannamei technology is superior at larger farms. Thereby, the paper is the first to provide a rationale for the continued coexistence of L. vannamei and P. monodon farming.

#### 3.3. Implication of findings

The implications of the findings are important along four directions. First, the identified increasing returns to scale in L. vannamei farming indicate that investments in extensions of large farms may be economically advantageous and may drive continued productivity growth. This favors an increasing global production of L. vannamei compared to P. monodon.

Second, while increasing returns to scale is identified also in the farming of P. monodon, it is only superior to L. vannamei when produced in smaller farms, as reflected by the FD measure that tends to be low for small farms, indicating that P. monodon is superior at smaller farm sizes. This implies that investments in small P. monodon farms, specialized in supplying large-sized shrimp to the world market at a premium price, is economically advantageous. However, the export earnings from P. monodon may be more fluctuating than that from L. vannamei because large-sized shrimp to a larger extent is a luxury good, so its demand is more affected by peaks and lows in the world economy than that for the smaller L. vannamei shrimp.

Third, although it remain an issue for future research, the results indicate that growth of the two species might be achieved in different ways. The reason is that the extensive production of P. monodon depend on the natural feed base available at the farms, which increase with space. Conversely, the intensive production of L. vannamei depends on the added feed with space being of less importance. That point toward that more space, and thereby investments in new small-scale farms, are needed for growth in production of P. monodon, while production of L. vannamei at larger farms can grow by adding extra seed and feed and thereby farm at higher densities at existing farms. To achieve growth, marginal revenue must exceeds marginal costs of the extra production in both types of production, implying that in farming of P. monodon, small-scale farms must be able to absorb investment costs in new farms, while in production of L. vannamei, larger farms needs to increase revenue more than seed and feed costs.

Fourth, the identified industry structure, where it seems appropriate both to expand L. vannamei production on large farms and continue P. monodon production at small farms, indicate that an optimal aquaculture policy must strive at offering proper framework conditions for

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\(^3\) Note that, the permutation test for frontier difference when using other returns to scale assumptions than CRS can result in undefined between-group efficiency scores (when an observation belonging to one group is compared to the frontier estimated based on the observations from the other group). This problem does, however, not occur for any observations in any of the 100 × 1000 combinations of jackknifed permutations done here, so it is simply ignored.

\(^4\) Or at least not inferior possibilities, because the frontiers coincide for some producers.
the benefit of both types of farms in order to exploit the full potential of the shrimp farming industry.

Finally, the larger and more intensive the farms becomes the more important bio-security and optimization of input use becomes. This is due to the fact that the economic losses due to diseases in an optimal use of inputs, such as feed, also becomes large when farm size increase. Here it seems that L. vannamei have an advantage because pathogen free seed can be produced from domesticated broodstocks and that the feed conversion rate is better (Esparza-Leal et al., 2010; Shakir et al., 2014; Supono., 2021).

4. Conclusions

Increasing returns to scale in L. vannamei farming has been identified as a potential driver of the species composition change in Indonesia, where the main species produced has shifted from P. monodon to L. vannamei. Increasing returns to scale has also been found in the farming of P. monodon, however, the production have been more or less constant from 2004 to 2020 (FAO, 2022). This stagnation in P. monodon is due to the superiority of L. vannamei when it comes to larger scale farming, which is identified by using a production possibility frontier approach.

Although the P. monodon farms potentially can take advantage of increasing returns to scale and is superior in small scale farms, L. vannamei seems to be a superior production technology (species) at large scale farms. Some of the reasons for this superiority may be found in the ability to secure pathogen free seed from domesticated broodstocks and a more efficient use of feed in terms of a lower feed conversion rate. Therefore, L. vannamei has shown a tremendous growth and have overtaken large parts of the global shrimp market, but P. monodon prevails because of the benefits that can be reaped at smaller farm size.

On this basis, it is concluded that it is an advantage to extent production of L. vannamei farms when aiming for large monoculture production facilities producing large quantities. Either by increasing production at existing farms with higher use of feed and feed with farming at higher densities, or by investing in new farms. On the other hand, P. monodon offer an opportunity for investment in new small-scale polyculture farms focusing at supplying large-sized shrimp in minor quantities at a price premium.

It is also concluded that an optimal policy design should encompass an industry structure with both large L. vannamei farms and small P. monodon farms to exploit the full potential of the shrimp farming industry, taking into account the local value of polyculture farmers providing income and food security in local communities.

While this conclusion is achieved for Indonesian shrimp culture, it may hold for several other countries farming both species, since the global production pattern with rapid growth in L. vannamei and stagnation in the production of P. monodon seems to be a worldwide phenomenon. However, it remains a task for future research to investigate whether the conclusion drawn from the Indonesian case also holds for other countries.

The method of combining tests of IRS of different technologies (in this case shrimp species) with comparing production possibility frontiers of these technologies is broadly applicable to avoid incorrect conclusions on the appropriate industry structure. Having two species competing at the same global market, it is not enough just to rely on the test of IRS, because both technologies are found to exhibit IRS. However, when comparing production possibility frontiers, it is revealed that L. vannamei has an advantage to P. monodon when producing larger quantities in larger farms and vice versa for smaller farms. Thus, the optimal industry structure is a combination of large L. vannamei farms and small P. monodon farms.

CRediT authorship contribution statement

Mette Asmild: Conceptualization, Data curation, Formal analysis, Writing- original draft, Methodology, Validation, Writing- reviewing and editing. Venticia Hukom: Conceptualization, Investigation, Writing- original draft, Data curation, Writing- reviewing and editing. Rasmus Nielsen: Conceptualization, Investigation, Writing- original draft, Data curation, Writing- reviewing and editing. Supervision. Max Nielsen: Conceptualization, Investigation, Writing- original draft, Writing- reviewing and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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