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Stochastic bio-economic optimization of pond size for intensive commercial production of whiteleg shrimp *Litopenaeus vannamei*

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ABSTRACT

We used a stochastic bio-economic model to define the optimum pond size for intensive, commercial production of whiteleg shrimp *Litopenaeus vannamei*. Optimization is based on economic performance and minimization of risk of farms (approximately 50 ha each) using pond sizes from 2–8 ha. Ponds of 2 ha maximized Net Present Value (NPV), Internal Rate of Return (IRR) and Return per Unit Risk (RUR). Mean NPV varied from US$ −59,800 (8 ha pond size and 30% interest rate) to US$ 63,300 (2 ha pond size and 10% interest rate). RUR calculated for NPV varied from −7.96 (8 ha pond size and 30% interest rate) to 1.79 (2 ha pond size and 10% interest rate). Positive values of mean NPV and RUR were projected for pond sizes lower than 4 ha (20% interest rate) and 5.5 ha (10% interest rate). Negative values of mean NPV and RUR were projected for all pond sizes when the interest rate was 30%. The results, when calculating IRR and the corresponding RUR, confirmed that pond size of 2 ha is optimum. Mean IRR varied from −11.76% (8 ha pond size) to 25.31% (2 ha pond size), and RUR varied from −2.62 (8 ha pond size) to 2.87 (2 ha pond size). Attractive values of mean IRR were projected for ponds smaller than 4 ha when the Minimum Attractive Rate of Return (MARR) was 20% and 5.5 ha when the MARR was 10%. No attractive values of mean IRR were projected when the MARR was 30%. Mean negative values of IRR and RUR were projected for ponds larger than approximately 6.3 ha. For ponds of 2 ha, we determined that there are 95, 50, and 5% probabilities of obtaining a MARR of at least 11.8, 25.2, and 34.6%, respectively. Alternative sizes of farms composed of 2 ha ponds indicated that economic risk decreased as farm size increased from 4 to 25 ponds. Despite higher construction costs, 2 ha ponds are recommended because of their better economic performance, due to larger shrimp size and greater biomass at harvest.

1. Introduction

Designing a shrimp farm is a specific case of design of engineering systems. The optimum design for these systems can be a complex problem, requiring economic considerations and an interdisciplinary approach (Arora, 2012). In our study, we use a stochastic bio-economic model to find an optimum pond size for commercial, intensive production of whiteleg shrimp *Litopenaeus vannamei*. Optimization is based on economic performance and minimization of risk of farms using different pond sizes.

Construction and calibration of the bio-economic model for calculating annual net revenues for intensive cultivation of shrimp farms, above operation costs, are described by Ruiz-Velazco et al. (2010a, 2010b) andHernández-Llamas et al. (2011, 2013). The model served to calculate economic risk associated with white spot disease and stochastic variability in economic, zootechnical, and water quality parameters. A biological sub-model is part of the bio-economic model and its predictive power was tested using linear regression and equivalence tests (Ruiz-Velazco et al., 2010b, 2013). The results, using the bio-economic model, indicated that the highest stocking densities, longest duration of cultivation, early start of aeration during the production cycle, and ponds of minimum size (2 ha) maximized annual net revenues and minimized risk (Hernández-Llamas et al., 2013).

In those studies, investment costs (including construction costs) were not considered. Since construction costs per hectare increase as pond size is reduced (Adams et al., 1980; Treece, 2001), we hypothesized that the cost of construction would lead to an optimum pond size larger than 2 ha. In our current study, we used the bio-economic

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model previously described for calculating annual net revenues above operation costs and expanded the analysis to consider construction and other investment costs over a time span longer than one year.

We estimated investment costs for 50 ha intensive farms (each one using ponds with a fixed size) aimed at operating in State of Nayarit, Mexico. We consider these investment costs representative of intensive shrimp farms in large part of northwest Mexico, where almost the totality of shrimp production in Mexico is carried out. In 2012, shrimp farms in the State of Nayarit cultivated 6200 ha, produced 9600 t of shrimp with an economic value of USD$ 35 million (CESANAY, 2014). According to Ponce-Palafox et al. (2012), there are 220 semi-intensive and 9 intensive shrimp farms in Nayarit. Most of the semi-intensive farms (62.0%) range from 1 to 3 ponds (10 ha per pond is the average size), whereas intensive farms range from 1 to 42 ponds (3 ha per pond is the average size). Each farm averages five permanent employees, and additional personnel are employed during the harvesting period. Most of the farms (95%) are active, although the legal situation of many of them is uncertain. Physicochemical parameters typical of the lagoons in Nayarit are shown in Table 1.

Islam et al. (2005) and Milstein et al. (2005) calculated the benefit-cost ratio for small, medium, and large ponds (2, 6, and 54 ha) for giant tiger prawn (*Penaeus monodon*) cultivation in Bangladesh, although ponds of different sizes were managed in different extensive ways (from 85–204 kg ha^{-1}, without artificial aeration) and costs of construction were not considered in their analysis. According to these authors, higher net returns are obtained when operating small ponds, compared with large ponds. To our knowledge, there are no antecedents in the literature that specifically deal with design optimization of shrimp farms, using a stochastic bio-economic model and considering investment costs (including construction), to determine the most convenient pond size within the range size typically used for commercial intensive management.

In this study, we deal with design optimization of intensive shrimp farms by determining the optimum pond size from a bio-economic perspective for the conditions prevailing in the State of Nayarit, Mexico.

2. Materials and methods

The bio-economic model developed by Hernández-Llamas et al. (2013) was integrated with the following submodels and stochastic zootechnical and water quality parameters.

2.1. Biological submodel

The biological model predicts shrimp biomass as the product of individual mean weight of shrimp and the number of surviving shrimp at different harvesting times. Mean weight was predicted using the following equation:

$$w_n = w_i + \left(w_f - w_i\right)\left[\left(1-k^n\right)/\left(1-k^h\right)\right]^3 \tag{1}$$

where, w_n is the shrimp weight after n time events have passed, w_i is the initial weight, w_f is the final weight, k is the growth coefficient, and h is time events that have passed until harvesting time.

Table 1
Physicochemical parameters of lagoons in Nayarit (Sanchez, 1994).

Parameter	Annual variability
Temperature (°C)	22.5–34
Salinity (‰)	0–35
Dissolved oxygen (mg L^{-1})	1–7
Nitrite and nitrate (μM L^{-1})	3.6–48.6
Ammonium (μM L^{-1})	0–8.9
Orthophosphates (μM L^{-1})	0–1.1

Surviving shrimp was predicted for normal operating conditions (when cultivation is not affected by white spot disease), using:

$$n_t = n_0 e^{-z\,t}, \tag{2}$$

where, n_t is the number of surviving shrimp at time t, n_0 is the initial population, z is the mortality rate.

When cultivation was affected by white spot disease, the following equations were used:

$$n_t = n_0 e^{-z\,t}, \quad \text{for } t \le t_w, \text{ or} \tag{3}$$

$$n_t = \left(n_0 e^{-z1\,tw} - m\right) e^{-z2(t-tw-1)}, \quad \text{for } t > t_w \tag{4}$$

where, $z1$ is the mortality rate previous to t_w, t_w is the time when mortality caused by the disease occurs, m is the mortality caused by the disease and$z2$ is the mortality rate after t_w.

2.2. Feed conversion ratio submodel

This submodel predicts, for operations not affected by white spot disease, the feed conversion ratio as a function of time as:

$$FCR_t = a_F t + b_F \tag{5}$$

where FCR_t is the feed conversion ratio at time t and a_F and b_F are the regression coefficients.

When cultivation was affected by the disease, the following equations were used:

$$FCR_t = a_{F1} t + b_F \tag{6}$$

for $t \le t_w$, or

$$FCR_t = \left[\left(a_{F1} t_w + b_F\right) + i_F\right] + \left[a_{F2}\left(t - t_w - 1\right)\right] \tag{7}$$

for $t > t_w$, where, a_{F1} is the slope before t_w, b_F is the intercept, i_F is the increase in feed conversion ratio derived from mortality caused by the disease, and a_{F2} is the slope after t_w.

2.3. Aeration submodel

For operations not affected by white spot disease, this submodel predicts aeration as a function of time:

$$AT_t = A_0 + \frac{A_F - A_0}{1 + e^{d.(b-t)}} \tag{8}$$

where, AT_t is the total aeration at time t; A_0 is the initial aeration, A_F is the final aeration, d and b are regression coefficients. When cultivation was affected by white spot disease, the following equation was used:

$$AT_t = a_A t + b_A, \tag{9}$$

where, a_A and b_A are regression coefficients.

2.4. Submodels of parameters of the biological submodel and stochastic elements

Using multiple linear regression models, these submodels predict the values of parameters of the biological submodel as a function of water quality and management variables. Stochastic elements are incorporated as normal error distributions (ε) fitted to residual values resulting from regression analyses. Error distributions had mean (μ)