A stochastic approach for analysis of the influence of white spot disease, zootechnical parameters, water quality, and management factors on the variability of production of shrimp *Litopenaeus vannamei* cultivated under intensive commercial conditions

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**A B S T R A C T**

We investigated the variability of shrimp *Litopenaeus vannamei* production by incorporating stochastic elements into deterministic stock models and determined the contribution that white spot disease, zootechnical parameters, water quality, and alternative management strategies have on variability. The model was calibrated for intensive shrimp cultivation in the State of Nayarit, Mexico. Mean annual production increased as a consequence of improved management from 8000 kg ha\(^{-1}\) to 22,000 kg ha\(^{-1}\) when cultivation was not affected by the disease and from 3200 kg ha\(^{-1}\) to 10,400 kg ha\(^{-1}\) when the disease affected production. When simultaneously considering both cases, mean annual production increased from 6300 kg ha\(^{-1}\) to 16,800 kg ha\(^{-1}\). White spot disease was a major factor determining variability of production. Shrimp production was particularly sensitive to levels of dissolved oxygen when management was inadequate, while final weight and mortality rate of shrimp were more sensitive when management improved. Water temperature and salinity had intermediate importance, and mortality caused by the disease and the time when mortality occurred had intermediate or low relevance. Improving management increased shrimp production and diminished variability. The duration of cultivation and stocking density were the most important management variables controlling variability of production when cultivation was affected by the white spot disease. When the disease was not present, pond size and duration of cultivation were the main factors affecting production. Starting time of aeration had relatively lower importance in determining variability, while the stochastic values of dissolved oxygen, in contrast, became most important. These results call for studies on improving aeration management to reduce variability of dissolved oxygen in ponds.

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1. Introduction

Several studies have implicitly analyzed stochastic variability of shrimp production when conducting risk analysis from economic or bioeconomic perspectives (Griffin et al., 1981; Sadeh et al., 1986; Martinez and Seijo, 2001; Valderrama and Engle, 2002; Seijo, 2004; Hernández-Llamas et al., 2004; Sánchez-Zazueta and Martínez-Cordero, 2009). Yet, the mechanisms by which exogenous and management factors determine the stochastic variability of production is frequently overlooked. Insight into these mechanisms is necessary for understanding the complex processes in cultivating shrimp in ponds and improving management practices. In the reviewed literature, we did not find investigations specifically dealing with stochastic variability of shrimp production nor with the causes determining it.

In previous works using stock models when shrimp were cultivated under intensive commercial conditions, we explore the role that white spot disease, zootechnical parameters, water quality, aeration, pond size, stocking density, and duration of cultivation have in determining shrimp production (Ruiz-Velazco et al. 2010a,b). In those studies, we used a deterministic approach to separately study operating conditions, whether or not being...
affected by white spot disease. In this investigation, we incorporate stochastic elements into the analysis, considering the probability of occurrence of the disease, the stochastic variability of zootechnical and water quality parameters, and determined the contribution that these parameters and alternative management strategies have on variability of shrimp production. The stochastic model was calibrated for intensive farming located in the State of Nayarit, Mexico.

2. Materials and methods

2.1. Data survey

Data for the period 2004–2006 from two of the three intensively cultivated shrimp farms in Nayarit were used (Ruiz-Velazco et al., 2010a,b). There were 37 cases (ponds) operating under normal conditions (22 during winter, 15 during summer) and 49 ponds affected by white spot disease (37 during summer, 12 during winter). For each pond, the following variables were analyzed: shrimp growth, survival, shrimp biomass, initial stocking density (35–95 postlarvae m⁻²), pond size (0.6–8 ha), aeration rates (294–16145 H p h⁻¹), starting time of aeration (1–14 weeks), water temperature (26.03–32.42 °C), salinity (17.25–35.34 ppt), and dissolved oxygen (6.11–10.63 mg L⁻¹).

2.2. Stock model

We used the stock models described in Ruiz-Velazco et al. (2010a,b) to predict shrimp biomass per hectare at time t (B_t):

\[ B_t = W_t n_t, \]

where \( W_t \) is the weight of shrimp and \( n_t \) is the number of surviving shrimp.

The weight of shrimp is predicted by:

\[ W_t = W_1 + (W_f - W_1) \left( \frac{1 - e^{1/c}}{1 - e^{k/c}} \right)^3, \]

where \( W_1 \) is the initial weight, \( W_f \) is the final weight, \( k \) is the rate at which \( W_t \) changes from its initial value to its final value, and \( c \) is harvesting time.

For normal operating conditions, survival is predicted by the exponential equation:

\[ n_t = n_0 e^{-z t}, \]

where \( n_0 \) is the number of survivors, \( n_0 \) is the initial population, and \( z \) is the instantaneous mortality rate.

For survival when white spot disease is present, the equation is:

\[ n_t = n_0 e^{-z_1 t}, \quad \text{if } t \leq t_w \]

or

\[ n_t = (n_0 e^{-z_1 t_w} - m) e^{-z_2 (t - t_w)}^{-1}, \quad \text{if } t > t_w, \]

where \( n_0 \) is the population at the beginning of the cultivation cycle, \( z_1 \) is the instantaneous mortality rate previous to the time when die-off from disease started \( t_w \), \( m \) is mortality from disease (hereafter, mortality), and \( z_2 \) is the instantaneous mortality rate after \( t_w \).

2.3. Statistical and stochastic models

The multiple linear regression models used to predict parameter values of the stock models (Eqs. (2)–(5)), as a function of management and water quality variables, are presented in Table 1. The residual values from fitting the regression models were tested for normality (Shapiro–Wilk’s W-test), and stochastic values of each parameter in the stock model \( Q_1 \) were calculated with:

\[ Q_1 = Q + s, \]

where \( Q \) is the deterministic value of the parameter calculated from multiple regression equations in Table 1 and \( s \) is the stochastic element calculated from a normal distribution fitted to the corresponding residual error dataset.

Stochastic values of temperature and salinity in the equations in Table 1 were calculated from probability distributions (normal, logistic, or triangular) fitted to values of both variables contained in the databases. Dissolved oxygen was predicted as a function of starting time of aeration (the time when aerators are run for the first time during the production cycle; Table 2), and stochastic values of oxygen were calculated from normal probability distributions fitted to the residual errors resulting from fitting the equations in Table 2.

### Table 1

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_f = -16.1 + 2.807 - 0.795 )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( W_f = -24.0 + 0.0027 - 0.0311DO - 0.0006SD )</td>
<td>0.00070</td>
</tr>
<tr>
<td>( W_f = -79.6 + 1.867 + 3.76DO )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( m = 296.6 + 8.587 + 4.48DO + 0.995 )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( z_2 = 0.101 - 0.0085DO )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( W_f = -2.55 + 1.14DO - 0.235 - 0.0195 - 0.964PS + 1.656DC )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( k = 103 - 0.00637 + 0.012DO - 0.0009DC )</td>
<td>0.00001</td>
</tr>
<tr>
<td>( z = 0.04 - 0.000967 )</td>
<td>0.02950</td>
</tr>
</tbody>
</table>

Source: Ruiz-Velazco et al. (2010a,b).

* * * 

Affected by white spot disease.

### Table 2

<table>
<thead>
<tr>
<th>Equation</th>
<th>( P )</th>
<th>Production cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO = 9.33–0.17 STA</td>
<td>0.0003</td>
<td>Winter*</td>
</tr>
<tr>
<td>DO = 9.07–0.19 STA</td>
<td>0.00001</td>
<td>Summer*</td>
</tr>
<tr>
<td>DO = 10.18–0.68 STA</td>
<td>0.000246</td>
<td>Winter and summer</td>
</tr>
</tbody>
</table>

Source: Ruiz-Velazco et al. (2010a,b).

* * * 

Affected by white spot disease.

### Table 3

<table>
<thead>
<tr>
<th>Management strategy</th>
<th>SA (weeks)</th>
<th>Duration of cultivation (weeks)</th>
<th>Stocking density (postlarvae m⁻²)</th>
<th>Pond size (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>Winter*</td>
<td>Winter</td>
<td>Summer*</td>
<td>Summer</td>
</tr>
<tr>
<td>1 (worst)</td>
<td>5</td>
<td>7</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>6.5</td>
<td>13</td>
<td>13.25</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
<td>13</td>
<td>15.75</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5.5</td>
<td>13</td>
<td>17.75</td>
</tr>
<tr>
<td>5 (best)</td>
<td>1</td>
<td>5</td>
<td>13</td>
<td>20</td>
</tr>
</tbody>
</table>

SA = start of aeration, WS = winter and summer.

* * * 

Affected by white spot disease.
2.4. Simulation

Monte Carlo simulation was used to predict stochastic variability of shrimp production. Variability in production was measured using the coefficient of variation (Mun, 2006) when the probability distribution of shrimp production was unimodal, or the ratio (97.5th percentile–2.5th percentile) median$^{-1}$ when multimodal.

Significant correlations between parameter values were considered for simulation. The Latin hypercube sampling and mean values of the distributions (3% tolerance and 95% confidence levels) were employed to minimize sample size (number of iterations). Variability in production was simulated for two farm sizes, one constituted by a single pond of 2.5 ha and the other by twenty 2.5 ha ponds on a farm of 50 ha.

The occurrence of white spot disease was simulated based on historical records of the surveyed farms and the Comité de Sanidad Acuícola del Estado de Nayarit during 2001–2009. Testing for contingency and serial randomness (Zar, 2010) showed that the disease occurred at random, independent of season of cultivation (winter or summer) and year. The occurrence of the disease was simulated as follows: cases occurring in winter and summer (33%); cases occurring only in winter (11%) or in summer (11%); normal cases (45%). The percentage of infected ponds was 100% in winter and 70% in summer.

The effect of alternative management strategies on shrimp production was analyzed by determining, in a first step, the values of the management variables that minimized and maximized median production values and, in a second step, intermediate values of the management variables were used to define management strategies that produced intermediate levels of production (Table 3). We used RiskOptimizer v5.5 to determine the values of the management variables that minimized and maximized production.

2.5. Sensitivity analysis

Sensitivity of shrimp production to stochastic variability of zootechnical parameters and water quality variables was determined with multivariate stepwise regression, where the values of the regression coefficients indicate the sensitivity of production to inputs. Sensitivity analysis was also used for the management variables.

2.6. Software systems

Normality tests, regression analyses, correlation between parameters, and contingency and serial randomness tests were conducted using STATISTICA v6.0 and STATA v10, setting significance at $P < 0.05$. The stock model was programmed in worksheets of Excel 2007, the stochastic elements were programmed using @Risk v5.5, and @Risk Optimizer v5.5 was used to determine the worst and best management strategies. Procedures available in @Risk v5.5 were used for simulation and sensitivity analysis.

3. Results

There were important effects of the management strategies on shrimp production and values of the coefficients of variation. For a single pond affected by the disease, production varied from 200 kg ha$^{-1}$ to 1300 kg ha$^{-1}$ during the winter cycle and from 2800 kg ha$^{-1}$ to 8100 kg ha$^{-1}$ during the summer cycle (Fig. 1a). Under normal conditions, production varied from 2600 kg ha$^{-1}$ to 8500 kg ha$^{-1}$ during the winter cycle and from 3100 kg ha$^{-1}$ to 12,600 kg ha$^{-1}$ during the summer cycle (Fig. 1b). Values of the coefficient of variation indicated that variability of production decreased by improving management practices, particularly when the disease was absent.

The prediction of annual production showed that mean production increased and production variability diminished as management improved at small and large farms (Fig. 2). This occurred whether or not shrimp were affected by white spot disease. For any given management scheme, mean production was similar for small and large farms, although variability was lower for the larger farm (Fig. 2). Greater variability in production occurred when cultivation was affected by white spot disease, as indicated by larger values of the coefficient of variation (Fig. 2).

Annual production increased as a consequence of improved management practices. Production increased from 8000 kg ha$^{-1}$ to 22,000 kg ha$^{-1}$ when cultivation not affected by white spot dis-

![Fig. 1](image-url). Mean shrimp production as a function of management strategies, as defined in Table 3, calculated for (a) winter and (b) summer production cycles. Dashed lines indicate ±SD and the plotted values correspond to the coefficient of variation. WSD = operations affected by white spot disease, NO = normal operations (not affected by disease).
ease (Fig. 2a) and from 3200 kg ha⁻¹ to 10,400 kg ha⁻¹ when the disease was present (Fig. 2b). When simultaneously considering cases with and without infection, annual production increased from 6300 kg ha⁻¹ to 16,800 kg ha⁻¹ (Fig. 3). Probability distributions of annual production were mainly shaped by the probability of occurrence of the disease (Fig. 4). Bimodal distributions were obtained for the small farm, where the values grouped around the mode to the left of the distribution corresponded to production affected by the disease in both seasons or in winter (Fig. 4a and c). Production grouped around the mode to the right, corresponded to cases affected by the disease during the summer cycle or when the disease was absent in both seasons (Fig. 4a and c). The probability distribution of production for the large farm had four modes (Fig. 4b and d). From left to right, production was associated with events when the disease affected both cycles, only winter cycles, only summer cycles, and when the disease was absent. Variability was less as farm size increased and management improved.

Crops were particularly sensitive to DO when management was poor and the final weight and mortality rate of shrimp were more sensitive when management improved (Table 4). Water temperature and salinity had intermediate importance and mortality caused by the disease and the time when it occurred had intermediate or low relevance.

Sensitivity analysis at maximum reference points showed that duration of cultivation and stocking density were the most impo-
tant management variables controlling the variability of production during winter and summer cycles and when cultivation was affected by white spot disease (Fig. 5). The main management variables when cultivation was not affected by the disease were pond size in winter cycles and duration of cultivation in summer (Fig. 5).

4. Discussion

White spot disease was a major factor determining variability of intensive production of shrimp, regardless of the management strategy or the production cycle. Improving management, on the other hand, increased shrimp production and diminished variability, whether or not production was affected by the disease. There is no a priori reason to assume that management practices leading to increased production should necessarily produce less variability. In this study, however, we found that good management practices produced both benefits.

From probability distribution of production shown in Fig. 4, we observed that reduction in production variance was a consequence of better management and increased farm size. Small shrimp farms bear greater risk than large farms (Valderrama and Engle, 2002). In our study, production was computed as averages from single ponds, and lower coefficients of variation for the larger farm indicated reduction of variability compared with the small farm. In large farms, extreme variability observed in some ponds can be compensated by opposite extreme variability in other ponds. Reduction of variance for a large sample size is expected to occur according to the central limit theorem of statistics (Vose, 2001).

Maximum production was produced by combining high stocking densities, small ponds size, early start of aeration, and late harvesting. Stocking density is considered a risk factor for shrimp diseases because it increases the number of contacts (Kautsky et al., 2000). However, Leung et al. (2000) did not find a significant association between stocking density and disease when they analyzed risk factors for Asian shrimp farms. Corsin et al. (2001) did not find a relationship between stocking density and white spot disease during work with P. monodon. According to Soto and Lotz (2001), ingestion of infected dead shrimp is the most important mode of transmission of the disease. In our investigation, stocking density negatively influenced the final weight of shrimp when production was not affected by the disease (Table 1); reduction in production resulted from lower shrimp weight but this was balanced by the higher stocking density.

Small ponds have generally been recommended for shrimp cultivation (Hernandez-Llamas and Villarreal-Colmenares, 1999; Milstein et al., 2005; Magallon, 2006). We found that small ponds contributed to maximizing productions by increasing the weight of shrimp when the pond was not affected by white spot disease.

Aeration is used to improve water quality and enhance aquacultural production. Dissolved oxygen (DO) is directly related to aeration rate and is a major production factor in intensive production of shrimp (Hopkins et al., 1991). In this study, an early start of aeration had a major positive effect on production parameters (Table 1). As we demonstrated in a previous work, early aeration delays and mitigates shrimp mortality caused by white spot disease (Ruiz-Velazco et al., 2010b). In that investigation, we indicated that greater suspension of bottom sediments occurs when aeration is delayed, compared with levels of suspension when aeration is early and that it is likely that suspension of pond bottom sediments by aeration increases oxidation of ferrous radicals to ferric oxide and subsequently leads to oxidative stress in shrimp (Rameshthangam and Ramasamy, 2006; Mohankumar and Ramasamy, 2006). Depressed respiratory activity in infected shrimp will lead to greater vulnerability when dissolved oxygen is low.

There is no a priori reason to assume that production should consistently rise as the duration of cultivation increases, although we calculated the maximum biomass for the longest cycle of cultivation. As was expected, extended cultivation led to larger shrimp, but shrimp mortality was unaffected.

High temperature (32–33 °C) increases survival of juvenile L. vannamei infected with white spot disease (Vidal et al., 2001; Rahman et al., 2006). WSSV was more prevalent in Ecuadorian populations of L. vannamei during the winter (Rodriguez et al., 2003). For Marsupenaeus japonicus, Guan et al. (2003) found significantly lower concentrations of WSSV at 31 °C, compared to concentrations at 23 °C and 28 °C. In this study, increasing temperature positively affected the weight of shrimp and reduced mortality caused by WSSV.

Liu et al. (2006) show that stress from lowering salinity (from 22 to 14 ppt in 1 h) increases the white spot syndrome viral load in Fenneropenaeus chinensis. In our study, lower salinity was associated

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Table 4

Sensitivity analysis of shrimp production to stochastic variation of parameters of the stock model and water quality variables. The higher the absolute value of RC, the higher the sensitivity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Winter</th>
<th>Summer</th>
<th>Winter*</th>
<th>Summer*</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>0.82</td>
<td>0.64</td>
<td>0</td>
<td>0.64</td>
</tr>
<tr>
<td>O</td>
<td>0.5</td>
<td>-0.61</td>
<td>M</td>
<td>-0.52</td>
</tr>
<tr>
<td>Z</td>
<td>-0.23</td>
<td>0.37</td>
<td>z</td>
<td>-0.42</td>
</tr>
<tr>
<td>T</td>
<td>0.07</td>
<td>-0.17</td>
<td>T</td>
<td>0.32</td>
</tr>
<tr>
<td>K</td>
<td>0.00</td>
<td>0.07</td>
<td>S</td>
<td>-0.25</td>
</tr>
</tbody>
</table>

Best strategy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Winter</th>
<th>Summer</th>
<th>Winter*</th>
<th>Summer*</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>0.79</td>
<td>-0.75</td>
<td>0.99</td>
<td>0.69</td>
</tr>
<tr>
<td>O</td>
<td>0.48</td>
<td>0.52</td>
<td>S</td>
<td>-0.45</td>
</tr>
<tr>
<td>Z</td>
<td>-0.32</td>
<td>0.35</td>
<td>O</td>
<td>0.17</td>
</tr>
<tr>
<td>T</td>
<td>-0.17</td>
<td>-0.24</td>
<td>z</td>
<td>-0.16</td>
</tr>
<tr>
<td>K</td>
<td>0.00</td>
<td>0.00</td>
<td>M</td>
<td>0.00</td>
</tr>
</tbody>
</table>

RC = regression coefficients.

* Affected by white spot disease.
with lower mortality from the disease. We note, however, that in our study, the stressful effect from the drastic reduction in salinity was not analyzed, rather average values in individual ponds with independent shrimp populations were considered, which explains the overall effect of salinity during grow-out.

Low oxygen levels increase susceptibility of *L. stylirostris* and *P. monodon* to infectious diseases (Le Moullac et al., 1998). The results from sensitivity analysis showed that stochastic variability of DO is a major factor affecting production variability of *L. vannamei*, particularly when management is poor, or when production is affected by the white spot disease. These results confirm the one we obtained in a previous study showing, by means of a deterministic model, that late start of aeration resulted in low mean DO and increased susceptibility of shrimp to the white spot disease (Ruiz-Velazco et al., 2010b).

Variability in DO is related to two components: one is explained deterministically by the model that relates DO with starting time of aeration, and the other is the stochastic variability of DO that remains unexplained after fitting the model. Starting time of aeration had relatively lower importance in determining variability in shrimp production, compared with other management factors (Fig. 5). The stochastic values of DO, in contrast, were most important. These results call for studies to improve management of aeration to reduce variability of DO among ponds and increase confidence when forecasting production. Such studies should focus on pond design, especially impact interactions of pond size, depth, and geometry with wind speed and placement of aerators on mixing of pond water (Garcia and Brune, 1991).

In this investigation we showed the influence of alternative management strategies on variability of shrimp production. Inves-

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*Fig. 4.* Probability distributions of annual shrimp production. Whether white spot disease was present or not is considered simultaneously. The probability of 55% indicates the level beyond which production was not affected by the disease. (a) Management strategy 1 (2.5 ha); (b) management strategy 1 (50.0 ha); (c) management strategy 5 (2.5 ha); (d) management strategy 5 (50.0 ha).
tigations need be conducted with a bio-economic approach for optimal management of risk.

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