



Bio-economic analysis of super-intensive closed shrimp farming and improvement of management plans: a case study in Japan

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Abstract

Crustacean aquaculture is a multibillion-dollar industry worldwide that continues to show significant growth. Shrimp farming has been intensified for decades, and super-intensive closed culture systems have now been developed to improve productivity and reduce environmental burdens. Here, we used bio-economic approaches to investigate the mechanisms and economic productivity of shrimp farming. We used three steps: (1) path analysis by using structural equation models to determine the candidate factors associated with productivity; (2) modeling of population dynamics and profits; and (3) simulations based on the models to clarify the productive characteristics of a super-intensive closed culture system. Our findings suggest that the population dynamics of the system were limited by unidentified factors that differed from those found in many experimental studies, such as water temperature, salinity, dissolved oxygen, and nitrogenous waste. The unidentified factors were related to the number of days of rearing and cumulative biomass mortality. The production plan suggested by our simulation required frequent culture rotation to increase profits. Our case study provides important practical information about the characteristics of super-intensive shrimp farming, implications for efficient economic management, and new research subjects for the future.

Keywords Bio-economic · *Litopenaeus vannamei* · Population dynamics · Shrimp farming · Super-intensive aquaculture

Introduction

Shrimp farming is an important component of the aquaculture industry. In the decades followed by the first successful accomplishment of seed production in the penaeid shrimp *Marsupenaeus japonicus* (Hudinaga and Kittaka 1967), intensive shrimp farming has changed aquaculture around the world. Its use has steadily expanded to satisfy global

market demand; world shrimp production increased from 1.1 million to 4.9 million tons from 1999 to 2015 (FAO 2017). More than half of all shrimp consumed is based on aquaculture production (FAO 2017). Shrimp farming targets mostly penaeid shrimp, and up to 70% of cultured prawns are produced in countries such as Thailand, Indonesia, and Vietnam (FAO 2017). The high economic value of shrimp has generated a job market in shrimp farming, which thus plays an important economic role in supporting the livelihoods of people particularly in developing areas (Mialhe et al. 2013). As a result, shrimp farming is now a multi-billion-dollar industry worldwide that continues to show significant growth.

Despite these positive impacts, the growth of the industry has suffered many problems in recent years. Shrimp farms occupy between 1 million and 1.5 million hectares along the world's coastlines (Berlanga-Robles et al. 2011), and mangrove degradation is a major environmental consequence in American and Asian coastal areas. Almost half of the world's total mangrove land cover area has likely been depleted over the past 50 years (Curran 2002). Moreover, nutrient-laden effluent discharged from shrimp farms often

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causes the eutrophication of coastal waters. Such environmental pollution not only has a negative impact on the surrounding ecosystem, but also has the potential to decrease productivity by causing the deterioration of water quality, ultimately making environments toxic to shrimp (Thakur and Lin 2003). Another problem is recurrent disease outbreak. Shrimp populating intensive farms are subjected to more crowded conditions than those found in nature, and therefore, the environment of a typical farm is potentially stressful. There appears to be a link between environmental conditions and disease, although the precise nature of the relationship is complex and has yet to be elucidated (Snieszko 1973; Kautsky et al. 2000). Because of these environmental pollution and disease problems, the life span of a typical intensive shrimp pond seldom exceeds 5–10 years (Flaherty and Karnjanakesorn 1995; Dierberg and Kiattisimkul 1996).

Closed shrimp culture systems have been developed in recent years to mitigate the environmental burdens of effluent release and reduce the risk of disease. As such, super-intensive culture systems employing minimal exchange of rearing water are promising options for the execution of new aquaculture technologies (Schock et al. 2013). Super-intensive closed culture systems can conserve land and water resources and reduce the risks associated with habitat destruction, environmental pollution, and disease contamination. This type of shrimp farming is still being developed, and there are a variety of systems. Recent studies have tried to evaluate the optimal conditions for increasing biomass production (Wasielesky et al. 2006; Vinatea et al. 2010; Shi et al. 2011; Hostins et al. 2015). However, few studies have examined the balance of costs and benefits of closed-system culture under commercial production, and ways of attaining optimal economic management and addressing unforeseen problems when this type of aquaculture is adopted have not been sufficiently explored.

Simulations based on numerical models can provide insight into how to achieve better management strategies. Bio-economic modeling is one such satisfactory approach for studying the complex interactions among the different factors that affect aquaculture production (Llorente and Luna 2016). Along these lines, there are several examples of recent studies using bio-economic approaches that have been useful in improving strategies for shrimp farming in intensive and semi-intensive systems (Sanchez-Zazueta and Martinez-Cordero 2009; Sanchez-Zazueta et al. 2013; Gonzalez-Romano et al. 2014; Estrada-Pérez et al. 2015). In this study, we focused on the utility of such bio-economic approaches in improving management strategy for super-intensive closed culture shrimp production using the Indoor Shrimp Production System (ISPS) plant operating in Myoko City, Niigata Prefecture (Japan), as a case study. Here, we established new models specifically by analyzing population

dynamics in the actual production lanes of the ISPS plant. Our findings reveal the existence of factors that decreased productivity but were not identified in previous experimental studies; they also suggest improvements that could be made to subsequent production plans to deal with such factors.

Materials and methods

Data sources and case study site

We selected the Indoor Shrimp Production System (ISPS) shrimp plant located in Myoko City, Niigata Prefecture (Japan), as the case study site (operated by IMT Engineering Inc., Tokyo, Japan). Rearing data for eight batches, from February 2010 to September 2012, were provided by the operator of the aquaculture system (IMT Engineering Inc.). The target animal was *Litopenaeus vannamei*, which is the world's most commonly produced shrimp. The ISPS is a super-intensive closed culture system that circulates the rearing water; there is virtually no water inflow and outflow between the production lanes and the outside. Environmental factors can be easily maintained, as the control of this system is easier than that of conventional aquaculture systems that are not enclosed. Moreover, the price of the shrimp product has already been defined by cross-trading and does not change with market supply and demand, and shrimp products are generally sold out at every production cycle. We considered that this system contains few uncertain factors in terms of both farming and market conditions, making it preferable for analyzing the mechanisms of both aquacultural and economic production. For more detailed information, the reader is referred to supplementary materials and methods provided in the Online Appendix.

Concept of analysis and model specification

In order to establish a model for the purpose of optimizing production plans at the study site, we performed path analysis using structural equation modeling (SEM). This process involves screening the critical factors that determine the dynamics of shrimp production at the chosen study site by holistically analyzing the relationships among daily changes in environmental factors, rearing conditions, growth rates and mortality rates. We chose to focus on the grow-out stage of the production process (following the nursery phase), because shrimps largely increase in biomass during this phase, which is thus the most important part of the process to target in order to achieve overall improved production efficiency.

Based on the results obtained through path analysis, we next established models relating to population dynamics. Based on our SEM model, we firstly drew up a multiple

regression model by calculating shrimp mortality on a single day as inferred from cumulative dead biomass and time elapse. The results revealed by the SEM model were double-checked using multiple regression analysis. The Von-Bertalanffy growth model was used simultaneously for calculating biomass after model selection based on the Akaike information criterion (AIC). The living biomass could be calculated from daily changes in mortality, growth and the initial individual numbers of shrimp released into the production lane.

Harvesting models were established in order to estimate the profits related to shrimp production. Harvesting is also a means of controlling the population dynamics in an aquaculture setting by reducing future dead biomass via the process of culling. Accordingly, the harvesting model includes culling as a means of circumventing risk due to mortality, and improving overall yield, leading to economic gain. The economic yield can be directly calculated using the harvesting model independent of the influence of the shrimp market, because the price is fixed by cross-trading. The profit per single batch and the annual profit can be calculated based on the balance of the economic yield and the total cost required for production.

All parameters in the models were estimated with the least squares method. The models and the statistical tests used in this study are shown in the Online Appendix. The reader is referred to the model specification section in the Online Appendix for further information.

Aims of simulation methodology

Our simulations encompass two separate aims: (1) determining the direction of population control, and (2) drawing up the most suitable plans for shrimp production at the study site. Increases in accidental mortality and changes in growth rates were examined in the simulation for above-stated aim (1). The purpose of this simulation is to predict possible risks and foresee potential improvements that could be made to the process of shrimp production. To improve profits, there are therefore two possible options: (1) improve harvesting plans on the production side, or (2) alter shrimp prices and costs on the economic management side. We firstly simulated the harvesting plan that maximizes annual profit; thereafter, shifts in the harvesting plans were examined in response to cost and price settings. Detailed explanations are given in the Online Appendix.

Results

SEM model and the relationship between environmental factors and condition of shrimp

High fitness was observed using the model that presumed a relationship between changes in rearing conditions caused by elapsed time (Fig. 1; GFI=0.980; AGFI=0.951; RMSEA=0.020; $P>0.05$). The model structure put the number of rearing days as a variable at the center, and all other variables had direct or indirect paths from rearing days. The SEM model did not include variables associated with bacterial parameters (i.e. count of viable bacteria and *Vibrio* spp.), possibly because these parameters were not correlated with the number of rearing days. The growth rate was affected only by rearing days, via a latent variable. No environmental factor had paths to growth rate. We termed the latent variable “aging effects” from the path characteristics. Daily mortality was induced by latent variables related to rearing period and cumulative biomass mortality. Variables that have been studied as critical environmental parameters such as salinity, water temperature, dissolved oxygen, ammonia-N, nitrite-N, and nitrate-N showed no relationship to either growth rate or mortality. The other latent variables were termed “unidentified stress with elapsed time” and “unidentified stress with cumulative mortality.” The standardizing coefficient of unidentified stress with cumulative mortality on the path to daily mortality was approximately five times that of unidentified stress with elapsed time. The model indicated a strong tendency for mortality to induce further mortality in a chain reaction. Indicators of health were of two types: conditions induced by rearing days via unidentified stress with elapsed time, and a condition that depended on both the direct effects of rearing density and the indirect effects of rearing time via the latent variable, i.e., aging effects. The former were melanization on the body surface, blackening of the gills, and abundance of feed in the digestive tract. The latter was the loss of the second antenna. The effects of aging on antennal loss was 2.4 times the direct effect of rearing density. All health indicators had paths from the latent variables associated with conditions important for culture productivity, namely growth rate or daily mortality. However, no health conditions had paths to growth rate or mortality. This indicated that the observed health conditions were not the factors controlling these two items and worked simply as indicators of shrimp condition at the study site.

Simulation of population dynamics in response to changes in rearing conditions

Explanations of the models used in the simulation here, and the supporting values (estimated parameters, R^2 and

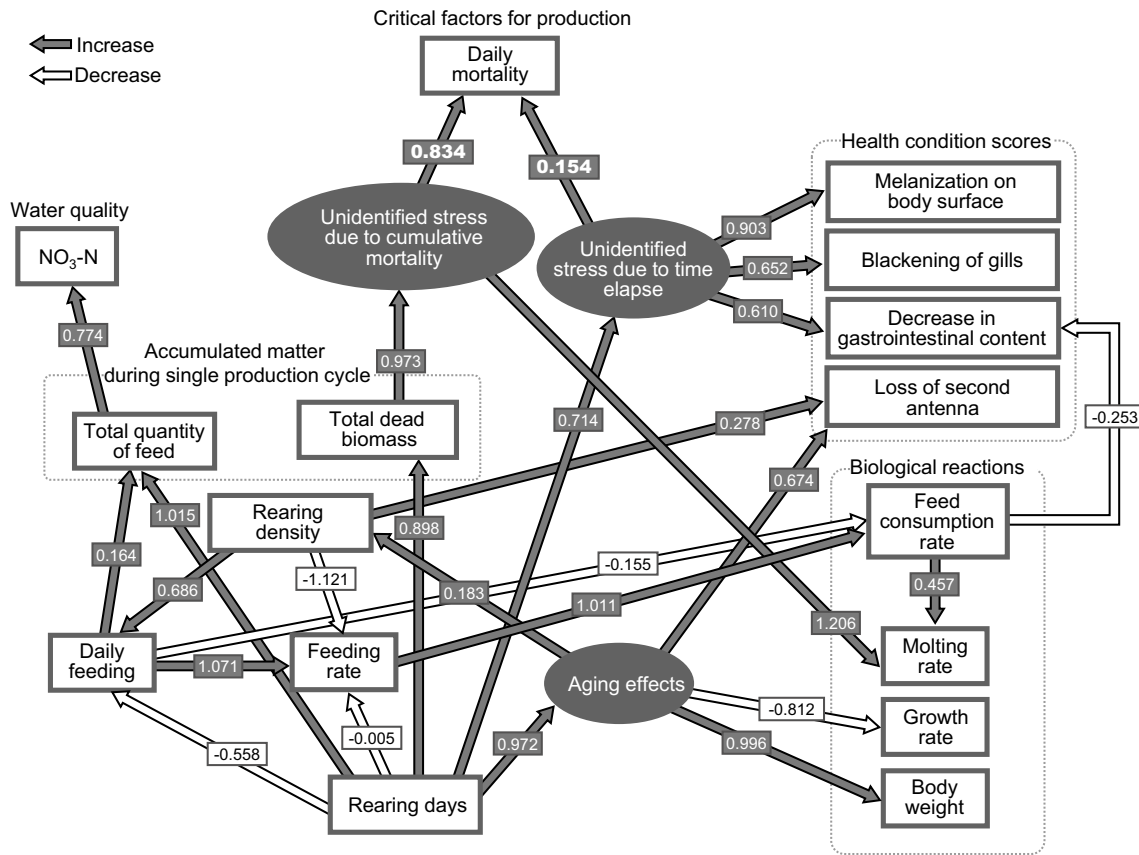


Fig. 1 SEM model evaluating the mechanisms causing daily mortality and changes in the health conditions of shrimp in pools at the study site. Solid squares indicate observable variables, and circles represent latent variables. Health conditions are expressed as scores.

Gray arrows indicate positive effects, and white arrows indicate negative effects. The numbers in the boxes are the standardizing coefficients at each respective path. The terms of error are not shown in this figure for purposes of simplicity

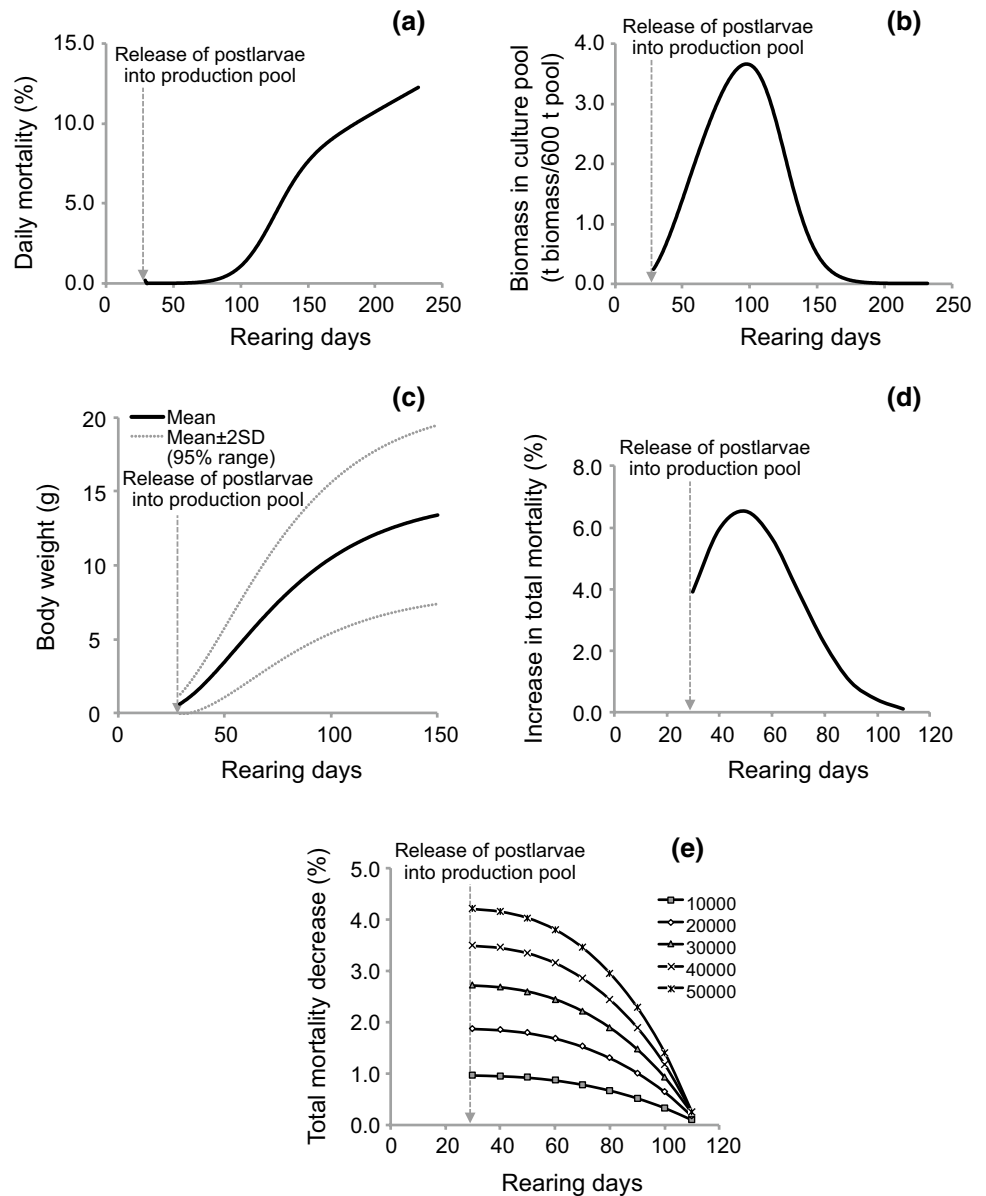
AIC) are described in the Online Appendix. Under conditions of no harvesting, biomass peaked at day 98 and then decreased, reaching zero on day 233 (Fig. 2a, b). Biomass dynamics comprised a balance between growth and mortality. Mortality was low at the beginning and then exponentially increased through an accumulation of biomass mortality, whereas the animals in the production lane grew linearly. Similarly, biomass peaked on a particular day and then decreased to zero when we used any value for n_0 and m_1 . The optimized number of shrimps harvested for maximization of total harvested biomass under a hypothetical constant harvesting number was 10,341 shrimps, which was slightly higher than the actual harvesting range, 5000–8000 shrimps. The beginning of harvesting was on day 79. The growth curve is shown in Fig. 2c. The total mortality at this time was 10.24%, which was lower than the actual mortality during a single run, $16.28 \pm 11.04\%$ (mean \pm SD). Considering the wide data ranges of the actual constant harvesting quantities and mortalities, the estimated values did not deviate far from the actual values. Therefore, to simulate population dynamics, the default

daily harvest was set at 10,000 (total rearing period is 114 days during a single run) as a good round number.

In the simulation evaluating the effects of accidental mortality increase, total mortality increased in response to an artificial 1% increase in mortality at any time (Fig. 2d). The increase in total mortality was higher in the early days of rearing; the highest increase was observed when the artificial increase in mortality was postulated on day 50. A single artificial 1% increase induced a 6.5% increase in total mortality on day 50. When accidental mortality was hypothesized to continue for 5 days (from days 50 to 54), total mortality peaked at 2.5 times that without an accidental increase in daily mortality (data not shown).

In the simulation in which we anticipated the potential effects of technological improvement or an unexpected decrease in growth rate, the growth coefficient K of Von-Bertalanffy's growth model (4) induced changes in total mortality. Total mortality was lowest when the value of K increased to +30% and highest when the value was -30% (Table 1). The increase in total mortality caused

Fig. 2 Estimated mortality (a) and population dynamics (b) when harvesting is not performed. Growth curve and the size range estimated by Von-Bertalanffy growth model (c). The 95% range indicates the body size range that includes 95% of all individuals according to Gaussian distribution. Increase in total mortality during a batch of production when the daily mortality is unexpectedly increased by 1% on one particular day (d). The critical period increasing the total mortality was predicted around 50 days after the beginning. Decrease in the total mortality per batch when shrimp were culled on one particular day (e). A single culling decreases several percentage of the total mortality in response to the amount and the timing



by the decrease in growth rate was more drastic than the improvement obtained by increasing growth rate.

Our simulation showed that artificial population subtraction reduced total mortality (Fig. 2e). The effect was almost constant at the beginning, but became exponentially smaller during the latter stages of rearing. The outcome also depended on how many individuals were subtracted from the population. Although the influence of the effects gradually decreased as the number for the subtraction increased, it seemed that there was a linear relationship between the number subtracted and the total mortality at a single time point.

Table 1 Maximum production and total mortality per batch when the growth coefficient *K* of Von-Bertalanffy’s growth model is changed

<i>K</i>	Production (t)	Total mortality (%)
+30%	3.97	6.3
+20%	3.86	7.2
+10%	3.73	8.7
±0%	3.58	10.7
−10%	3.38	13.4
−20%	3.12	18.7
−30%	2.78	24.8

Improved production plans and resulting profits

Using the equations given in the Online Appendix, we estimated the optimal harvesting conditions under current conditions at the study site. Our simulation results showed that the percentage of shrimp with a body size in the higher price class was extremely low under conditions in which profit was maximized either per batch or per year (Table 2). Optimization of harvesting to maximize profits per batch tended to slightly increase the percentage of higher-priced shrimp in summer, when heating was not required to maintain the temperature of the rearing water.

The harvesting plan for maximizing annual profit was the same under all seasonal conditions. Although there were negligible differences in both estimated harvesting plans, the optimized harvesting schedules concentrating on limited periods earlier than the end of actual harvesting indicated that the shrimp in the production lanes were best harvested when a sufficient percentage had reached a salable body size (Figs. 3, 4; Table 2). In contrast, total mortality during a single production cycle remained at a low level when an

early harvest was completed before the time of exponential increase in mortality (Table 2). These harvesting schedules were intended to maximize quantities and profits by raising the rotation rate per year, thus saving on costs for growth and reducing losses through mortality. However, the actual harvesting schedule at the study site did not match the conditions used in the theoretical schedule optimized for better economics (Fig. 4). The actual harvesting conditions were similar to those used to maximize the quantity produced in a batch, although actual harvesting was performed over a longer period. Data on actual profits are proprietary and cannot be reported here, but yield would be expected to be increased by 168% and costs by 126% according to our simulation maximizing annual profits. The 42% higher improvement in yield compared to that in costs predicts that annual profits can be largely improved by making use of our simulation plan proposed in this study.

Based on the comments of the operator of the case study site, this improved harvesting plan is expected to be feasible without making any changes to the working format and present facilities. The proposed plan is expected to result in

Table 2 Number of rearing days, total production, total mortality, and percentage of shrimp in salable condition, estimated by maximizing profits per batch and those per year

Season	Rearing days	Production (t/batch)	Mortality (%/batch)	Salable shrimps (%/batch)	Higher-priced shrimps that are salable (%)	Unsalable harvested shrimps (%/batch)
Maximizing profits per batch						
Spring/autumn	80	2.79	1.3	98.7	1.9	0.02
Summer	93	3.11	2.2	97.8	6.4	0.01
Winter	77	2.69	1.2	98.9	1.2	0.02
Maximizing profits per year						
Spring/autumn	75	2.60	1.0	99.0	0.8	0.02
Summer	75	2.60	1.0	99.0	0.8	0.02
Winter	75	2.60	1.0	99.0	0.8	0.02

Unsalable harvested shrimps indicate the estimated ratio of shrimps whose size is smaller than the minimum limit for sale, e.g., 3 g, among total harvested shrimps. The estimated harvesting plans for achieving these parameters are shown in Fig. 3

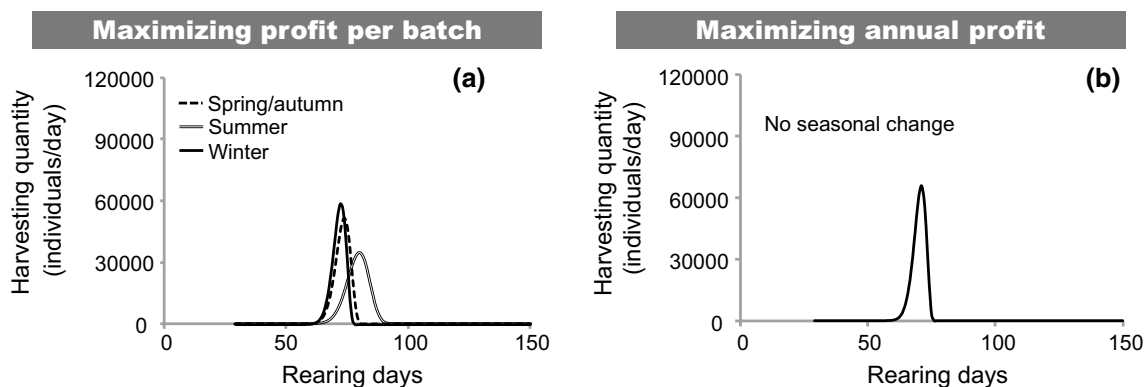


Fig. 3 Harvesting patterns to maximize profits per batch (a) and annual profits (b) corresponding to Table 2. Dotted lines indicate the optimized harvesting patterns in the spring/autumn season when optimized harvesting patterns in the summer or winter season are shifted

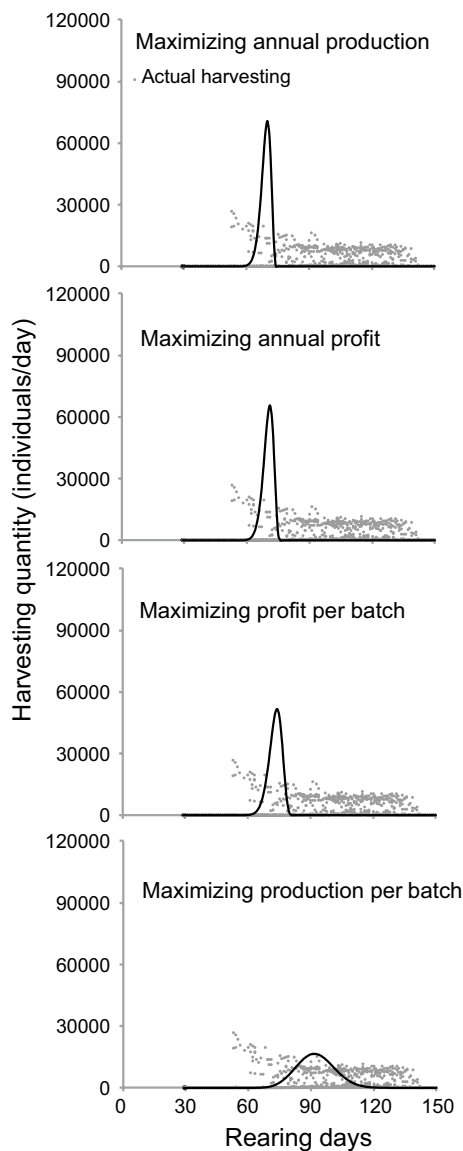


Fig. 4 Actual harvesting quantities and harvesting patterns to maximize annual production, annual profits, profits per batch and production per batch. Each plot indicates actual harvesting

a yield of small-sized class shrimp corresponding to more than 95% of the total product. There thus arises a difference in merchandising strategy for the two different-sized products; the small-sized class of merchandise is to be packaged as a batch of defined weight, whereas larger-sized shrimps are to be individually placed into packages. As a result, the improved harvesting plan can economize on working time at the study site, enabling the operation of the system to proceed smoothly without increasing the volume of labor, despite the increased level of production. Because the production concept proposed by this study puts forth that it would be valuable to produce smaller shrimp under higher rotation schemes, the proposed quantity of production is

within the storage capacity and floor space of the current processing facilities. Thus, our suggestions for improving the production plan are supported by both statistical analysis and actual operating conditions.

The changes in the optimized harvesting plans, and thus total rearing days, were estimated to differ between cost-down effects and price controls. No changes were observed when the total cost was changed (Fig. 5a, d). On the other hand, a price increase shifted the harvesting curve estimated in our study. The changes in the price increase in the shrimps in the higher price class induced drastic increases in the harvesting period from +4142 yen/kg (Fig. 5b, e). The increase reached a plateau when the price increase at the body size class was +6733 yen/kg, indicating a complete shift of the harvesting pattern for producing larger shrimps. Without considering any actual processes for price formation, this suggests that the appropriate price of the larger size class is 6642–9142 yen/kg to achieve maximal economic profits as long as the shrimp plant operator plans to produce larger shrimps, although the present price of this category is 3500 yen/kg. Harvesting plans focused on basic price setting were characterized into three types: an early, concentrated harvest; a late, prolonged harvest; and an intermediate type (Fig. 5c, f). The three types were relative to the current price setting, and the simulation result at the current, basic price belonged to the intermediate type. The early, concentrated harvesting pattern aimed to lower the total cost of growth and the risk of mortality. The change to this type had an inflection point at which the graph pattern jumped from one type to another. The jumping point was between 5230 yen/kg and 5231 yen/kg. In contrast, a late, prolonged harvest seemed to occur if the grower waited for the shrimp to reach a larger size. The change to this type showed several jumping points for complete shifting between 851 yen/kg and 2255 yen/kg. The largest change occurred between 1149 yen/kg and 1050 yen/kg. The change in the optimized harvesting pattern in response to the trial decreasing the basic price reached a plateau when the basic price was 850 yen/kg. Thereafter, the harvesting plan became completely the same as that seen in the trial changing the price of the larger size class. This indicates that the harvesting plan producing the larger size class can serve as a better choice only when the ratio of the basic price is sufficiently low against the price increase at the level of 1000 yen/kg.

Discussion

Since the initial success of artificial seed production for *M. japonicus* more than 50 years ago (Hudinaga and Kittaka 1967), shrimp farming has expanded worldwide. Many biological studies—especially those focused on physiological and pathological aspects—underpin the establishment of

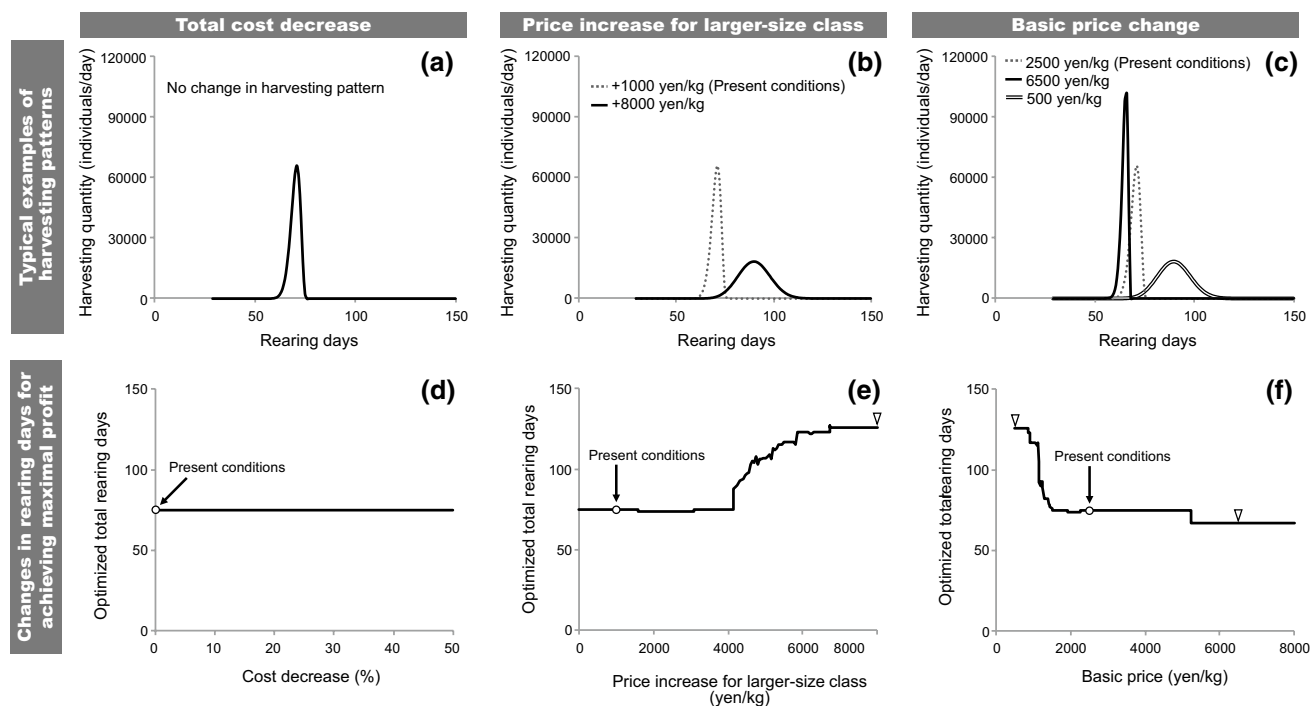


Fig. 5 Changes in harvesting patterns and changes in total rearing days according to decreasing the total costs (**a**, **d**), increasing the price of higher-priced shrimp (**b**, **e**) and increasing the basic price of shrimp (**c**, **f**). Dotted lines indicate the optimized harvesting patterns for the present condition when the optimized harvesting patterns for the target condition shifted from that point (**b**, **c**). White arrows in **e**, **f** indicate the price conditions chosen for simulating the harvesting conditions presented in **b**, **c**. The upregulation of the price increase for shrimps in the higher price class extended the optimized harvesting period, enabling the production of more shrimps belonging to

the higher price class. Drastic changes relating to harvesting period started when price increase was > 4142 yen/kg, and reached a plateau when the price increase at the body size class was > 6733 yen/kg (**e**). Harvesting plans focused on basic price setting were characterized as three types: an early, concentrated harvest; a late, prolonged harvest; and an intermediate type. The jumping point shifting from the intermediate type to the early, concentrated type was between 5230 yen/kg and 5231 yen/kg. The change from the intermediate type to the late, prolonged type showed several jumping points for complete shifting between 851 yen/kg and 2255 yen/kg (**f**)

commercial shrimp farming and are still ongoing for the purpose of improving aquaculture production. However, the importance of the final economic output of the commercial industry has been less well considered in the research field. Here, we tried to formulate an optimal aquaculture strategy by using bio-economic models. This approach has an advantage in that it can be used to analyze complex interactions of various factors in the actual processes of commercial aquaculture production and thus has implications for the industry's economic management. We applied the methodology to an indoor closed culture system, which is becoming a new candidate for intensive shrimp farming.

Our first analytical step using SEM evaluated aquaculture problems in an indoor closed super-intensive culture system, because it is possible that as-yet-unknown issues in rearing conditions will surface in this type of system (Fig. 1). Many studies have focused on the importance of chemical and physical environmental conditions limiting or decreasing productivity in shrimp farming; such conditions include salinity, water temperature, dissolved oxygen, and nitrogenous wastes (Wyban et al. 1995; Lin and Chen 2003;

Li et al. 2007; Yan et al. 2007; Pan et al. 2007; Furtado et al. 2015). However, our SEM model indicated that none of these conditions functioned to decrease productivity, as most of these parameters were maintained within acceptable levels in the production lanes used in our study. The notable point in our SEM model was the predicted major effect of cumulative mortality on daily mortality. The prediction given by the SEM model was supported by our multiple regression analysis. This means that mortality leads to further mortality, and that production loss increases in a chain reaction once mortality is triggered in the population. There is no information about the unidentified environmental factors critical to these kinds of shrimp farming systems. If the use of super-intensive closed systems is to be promoted, then we must accept that it will be essential in the future to clarify what these unidentified environmental factors are.

Modeling and simulation are general approaches for estimating and anticipating possible phenomena in particular situations. Although the above-mentioned environmental factors remain unidentified, simulations based on mathematical models can be used to provide improved plans in order

to avoid the economic losses that these factors may cause. Here, we established new models specific to this purpose. The simulations performed with our models have important implications for both biological and economic management.

Simulations changing the parameters comprising population dynamics showed the importance of population management and its details. The early part of the mortality curve was sensitive to an unexpected increase in mortality (Fig. 2d). It is therefore important to control mortality by maintaining rearing conditions. It is generally known that most aquatic animals have higher mortality rates in their early growth stages than in the later stages (Chockley and St. Mary 2003; Avella et al. 2010). Moreover, it has been reported that mortality in shrimp is increased by bacterial stress but eventually stabilizes (Thompson et al. 2010; Ng et al. 2015). The factors increasing this mortality remain unclear. However, our findings support reports showing the importance of controlling mortality in the early life stages. Our simulation also showed the importance of growth control (Table 1). Our results emphasized the serious productive loss caused by an accidental growth decrease—more than the predicted productive gain from growth improvement. Growth decrease delays the start of harvesting. This delay prolongs the farming schedule for a single run and increases the risk of production loss through mortality. The results of both simulations (Fig. 2d and Table 1) therefore indicate the importance of controlling biomass-scale population dynamics to prevent chain-reaction-type production losses. Artificial population subtraction may be one of the most effective management methods for controlling populations (Fig. 2e). The estimated effect is high when the mortality curve is sensitive to the unexpected increase in mortality, suggesting the efficacy of using population subtraction during the critical period. Our results showed the importance of having a proper harvesting plan to achieve successful biological population management. The effects of the stocking population on production is a common interest found throughout biological and bio-economic studies in aquaculture (Pardy et al. 1983; Araneda et al. 2008; Sanchez-Zazueta et al. 2013). This is similarly shown in our results, but our finding differs in that it indicates the utility of population control as a method for preventing exponential production loss.

Our optimized harvesting plans recommended earlier and concentrated harvesting to secure economic improvement (Figs. 3, 4; Table 2). These plans maximize the difference between economic yield through growth and production loss through death. Optimized plans that shortened the total period required for a single culture run indicated that faster rotation led to better economic profits as well. A faster rotation plan produced a 68% increase in annual economic yield in return for a 26% increase in each running cost. Faster production rotation has often been indicated as an effective means of achieving economic improvement in commercial

shrimp culture, although the details of the estimations differ (Yu et al. 2006). The production plan optimized here showed the possibility of drastically improving profits. However, the percentage of shrimp belonging to the body size class that was sold at higher prices was extremely low, especially in the case of maximizing annual profit (Table 2). This indicates that the economic yields from the larger and higher-priced shrimps cannot compensate for the increased costs of growth and the production losses caused by mortality during the prolonged rearing period for these larger shrimps. Actual harvesting at the study site was more similar to the harvesting plan that maximized production per batch rather than annual profit (Fig. 4). This suggests that the harvesting plan at the study site has not been optimized for economic gain. Nevertheless, the operator of the study site has tended to produce larger shrimp without considering economic loss, and it has repeated this production plan without changing its direction for at least 2 years.

One of the reasons is assumed to be the belief of the workers at the study site that production of the larger shrimp creates brand power. The aim of our simulations was to show how the production of these larger shrimp could be beneficial, focusing on price setting and the required decreases in production costs. Changes in the price setting shifted the harvesting plans to those with a long enough rearing period to produce shrimp of higher price and size, whereas a cost decrease did not affect the harvesting plans (Fig. 5). The price shifts prolonging the culture period indicated that changes in price might be good strategies for both improving profits and maintaining the perceived brand image achieved by production of the larger shrimp. The price of the large size class would need to be increased to a level sufficient to change the optimized harvesting plan, because the effect of the increased price on the optimization caused the thresholds to jump from one type of plan to the other. If the operator of the study site wishes to produce larger shrimp while minimizing its economic loss, the price for the size class will need to be increased by at least 90% compared with the present price. Although such large price increases do not seem feasible, there should be a margin of demand enabling this price increase, because the shrimp products are sold out at every productive cycle. The present plan attempting to produce larger shrimps is only acceptable when the basic price is much lower than the price increase at the larger size class. Given these findings, the plant operator's repeated choice of its present harvesting and price-setting policies implies that, because of the perceived brand-producing power of the larger shrimp, it is accepting the loss of opportunities to increase its profits. "Brand" is actually an attribute that is effective in increasing trading prices, even in fish products (Roheim et al. 2007; Ishida and Fukushima 2010; Bronnmann and Asche 2016). Similarly to what the staff at the study site believes, it has been reported that product size is

a factor supporting fish brand image (Bronnmann and Asche 2016). The company at the study site has succeeded in establishing its own, original brand with higher prices through their original farming system. In such a case, there is often a first-mover competitive advantage (Ishida and Fukushige 2010). However, it is not clear in this case whether the benefits obtained from the brand image are equivalent to, or more valuable than, the predicted opportunistic cost to maintain the brand image. As long as the plant operator believes in the brand power brought by the production of larger shrimp, there is another problem: how much production is required to maintain the brand image? This is an important point in clarifying why the plant operator repeatedly chose the present strategy and is important in relation to the plant operator's future acceptance of suggested plans for improving economic management.

As delineated throughout the manuscript, we used simulations based on bio-economic models to show the factors predicted to cause shrimp mortality in a super-intensive closed culture system, and we produced improved plans for maximizing profits at the study site. Our study suggests that an as-yet-unidentified factor relating to cumulative mortality in the closed system is especially critical in causing death, and we propose that the identification of this factor will be an important research subject for the future. Another important finding was that economic management itself functions as a form of shrimp population control that is effective in reducing production losses in the presence of the unidentified factor. Our analysis suggests that the company at the study site had a potential mismatch between the best economic strategies and actual production. The improved production schedule suggested here might achieve a dramatic increase in the profits of shrimp culture by earlier and more concentrated harvesting in super-intensive closed culture systems. In conclusion, this case study has demonstrated the utility of bio-economic information in analyzing such production systems; our approach may open new possibilities for the use of bio-economic modeling, for example, to design and develop an algorithmic package to control the actual production of shrimp on-site.

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References

- Araneda M, Pérez EP, Gasca-Leyva E (2008) White shrimp *Penaeus vannamei* culture in freshwater at three densities: condition state based on length and weight. *Aquaculture* 283:13–18
- Avella MA, Olivotto I, Silvi S, Place AR, Carnevali O (2010) Effect of dietary probiotics on clownfish: a molecular approach to define how lactic acid bacteria modulate development in a marine fish. *Am J Physiol Regul I* 298:359–371
- Berlanga-Robles CA, Ruiz-Luna A, Bocco G, Vekerdy Z (2011) Spatial analysis of the impact of shrimp culture on the coastal wetlands on the Northern coast of Sinaloa, Mexico. *Ocean Coast Manag* 54:535–543
- Bronnmann J, Asche F (2016) The value of product attributes, brands and private labels: an analysis of frozen seafood in Germany. *J Agric Econ* 67:231–244
- Chockley BR, St. Mary CM (2003) Effects of body size on growth, survivorship, and reproduction in the banded coral shrimp, *Stenopus hispidus*. *J Crustac Biol* 23:836–848
- Curran S (2002) Migration, social capital and the environment: considering migrant selectivity and network in relation to coastal ecosystems. *Popul Dev Rev* 28:89–125
- Dierberg FE, Kiattisimkul W (1996) Issues, impacts, and implications of shrimp aquaculture in Thailand. *Environ Manag* 20:649–666
- Estrada-Pérez M, Ruiz-Velazco JMJ, Hernandez-Llamas A, Zavala-Leal I (2015) A bio-economic approach to analyze the role of alternative seeding-harvesting schedules, water quality, stocking density and duration of cultivation in semi-intensive production of shrimp in Mexico. *Lat Am J Aquat Res* 43:466–472
- FAO (Food and Agriculture Organization of the United Nations) (2017) FishStatJ: software for fishery statistical time series. Version 3.03.2. FAO Fisheries and Aquaculture Department, Statistics and Information Branch. FAO, Rome
- Flaherty M, Karnjanakesorn C (1995) Marine shrimp aquaculture and natural resource degradation in Thailand. *Environ Manag* 19:27–37
- Furtado PS, Campos BR, Serra FP, Klosterhoff M, Romano LA, Wasielesky W (2015) Effects of nitrate toxicity in the Pacific white shrimp, *Litopenaeus vannamei*, reared with biofloc technology (BFT). *Aquac Int* 23:315–317
- Gonzalez-Romano MA, Hernandez-Llamas A, Ruiz-Velazco JMJ, Plascencia-Cuevas TN, Nieto-Navarro JT (2014) Stochastic bio-economic optimization of pond size for intensive commercial production of whiteleg shrimp *Litopenaeus vannamei*. *Aquaculture* 433:496–503
- Hostins B, Braga A, Lopes DLA, Wasielesky W, Poersch LH (2015) Effect of temperature on nursery and compensatory growth of pink shrimp *Farfantepenaeus brasiliensis* reared in a super-intensive biofloc system. *Aquac Eng* 66:62–67
- Hudinaga M, Kittaka J (1967) The large scale production of the young Kuruma prawn, *Penaeus japonicus* Bate. *Inf Bull Planktol Jpn Commemoration Vol., Dr. Matsue's 60th Birthday* 35–46
- Ishida T, Fukushige M (2010) The effects of fishery harbor-based brands on the brand equity of shore fish: an empirical study of branded mackerel in Japan. *Food Policy* 35:488–495
- Kautsky N, Ronnback P, Tedengren M, Troell M (2000) Ecosystem perspectives on management of disease in shrimp pond farming. *Aquaculture* 191:145–161

- Li E, Chen L, Zeng C, Chen X, Yu N, Lai O, Qin J (2007) Growth, body composition, respiration and ambient ammonia nitrogen tolerance of the juvenile white shrimp, *Litopenaeus vannamei*, at different salinities. *Aquaculture* 265:385–390
- Lin Y, Chen J (2003) Acute toxicity of nitrite on *Litopenaeus vannamei* (Boone) juveniles at different salinity levels. *Aquaculture* 224:193–201
- Llorente I, Luna L (2016) Bioeconomic modelling in aquaculture: an overview of the literature. *Aquac Int* 24:931–948
- Mialhe F, Gunnell Y, Mering C (2013) The impacts of shrimp farming on land use, employment and migration in Tumbes, northern Peru. *Ocean Coast Manag* 73:1–12
- Ng WK, Koh CB, Teoh CY, Romano N (2015) Farm-raised tiger shrimp, *Penaeus monodon*, fed commercial feeds with added organic acids showed enhanced nutrient utilization, immune response and resistance to *Vibrio harveyi* challenge. *Aquaculture* 449:69–77
- Pan L, Zhang L, Liu H (2007) Effects of salinity and pH on ion-transport enzyme activities, survival and growth of *Litopenaeus vannamei* postlarvae. *Aquaculture* 273:711–720
- Pardy CR, Griffin WL, Johns MA, Lawrence AL (1983) A preliminary economic analysis of stocking strategies for penaeid shrimp culture. *J World Maric Soc* 14:49–63
- Roheim CA, Gardiner L, Asche F (2007) Value of brands and other attributes: hedonic analysis of retail frozen fish in the UK. *Mar Resour Econ* 22:239–253
- Sanchez-Zazueta E, Martinez-Cordero FJ (2009) Economic risk assessment of a semi-intensive shrimp farm in Sinaloa, Mexico. *Aquac Econ Manag* 13:312–327
- Sanchez-Zazueta E, Hernandez JM, Martinez-Cordero FJ (2013) Stocking density and date decisions in semi-intensive shrimp *Litopenaeus vannamei* (Boone, 1931) farming: a bioeconomic approach. *Aquac Res* 44:574–587
- Schock TB, Duke J, Goodson A, Weldon D, Brunson J, Leffler JW, Bearden DW (2013) Evaluation of Pacific white shrimp (*Litopenaeus vannamei*) health during a superintensive aquaculture growout using NMR-based metabolomics. *PLoS One* 8:e59521
- Shi Y, Zhang G, Liu J, Zhu Y, Xu J (2011) Performance of a constructed wetland in treating brackish wastewater from commercial recirculating and super-intensive shrimp growout systems. *Biore-sour Technol* 102:9416–9424
- Snieszko SF (1973) Diseases of fishes and their control in the US. The two lakes fifth fishery management training course report. Jansen, London, pp 55–66
- Thakur DP, Lin CK (2003) Water quality and nutrient budget in closed shrimp (*Penaeus monodon*) culture systems. *Aquac Eng* 27:159–176
- Thompson J, Gregory S, Plummer S, Shields RJ, Rowley AF (2010) An in vitro and in vivo assessment of the potential of *Vibrio* spp. as probiotics for the Pacific White shrimp *Litopenaeus vannamei*. *J Appl Microbiol* 109:1177–1187
- Vinatea L, Gálvez AO, Browdy CL, Stokes A, Venero J, Haveman J, Lewis BL, Lawson A, Shuler A, Leffler JW (2010) Photosynthesis, water respiration and growth performance of *Litopenaeus vannamei* in a super-intensive raceway culture with zero water exchange: interaction of water quality variables. *Aquac Eng* 42:17–24
- Wasielkesky W, Atwood H, Stokes A, Browdy CL (2006) Effect of natural production in a zero exchange suspended microbial floc based super-intensive culture system for white shrimp *Litopenaeus vannamei*. *Aquaculture* 258:396–403
- Wyban J, Walsh WA, Godin DM (1995) Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp (*Penaeus vannamei*). *Aquaculture* 137:267–279
- Yan B, Wan X, Cao M (2007) Effects of salinity and temperature on survival, growth, and energy budget of juvenile *Litopenaeus vannamei*. *J Shellfish Res* 26:141–146
- Yu R, Leung PS, Bienfang P (2006) Optimal production schedule in commercial shrimp culture. *Aquaculture* 254:426–441
- Zar JH (1984) Data transformations. In: *Biostatistical analysis*. Prentice Hall, Englewood Cliffs, pp 236–243

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