Mathematical Modeling of the Growth of Chinese Shrimp (*Fenneropenaeus chinensis*) in High Density Stocking Pond

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Keywords: *Fenneropenaeus chinensis*, simulated modeling, shrimp aquaculture, sensitivity parameter

Abstract. Shrimp aquaculture is evolving from traditional open low stocking density to closed high stocking density in China. However, high density closed stocking ecosystem with eutrophication deteriorates the stocking environment of shrimps. A dynamic model simulating the growth of Chinese shrimps (*Fenneropenaeus chinensis*) was constructed based on the experimental data on field shrimp stocking to simulate and reflect the relationship among shrimp growth, pond ecosystem and artificial control to predict the potential risks and intervention of artificial control in macroscopic view in the production of shrimps in high density stocking pond using the ecological modeling software STELLA® 5.1.1. Seven growth parameters of shrimp were established; of which, two sensitive parameters, manual feeding and water temperature, were identified after parameter sensitivity test by Single Factor Analysis. The model was verified experimentally in the field. The model demonstrated that the growth of *Fenneropenaeus chinensis* was successfully simulated in a 90-day stocking circle in a high density pond. The two sensitive parameters indicated that the handling and manipulation of the manual feeding at different water temperature directly influenced the shrimp growth and production.

Introduction

Mathematical modeling is a quantitative analysis emerged in the 21st century for the exploration of the structure, functions, and growth pattern of aquatic organisms in pond aquaculture [1]. Compared with natural ecosystems, shrimp stocking pond is a closed ecosystem with high degree of manipulation of aquaculture measures such as manual feeding, fertilization, and mechanical aeration have significant impacts on the growth pattern of shrimps and the internal structure of pond system, leading to the aquatic ecosystems become more complicated. The technique simulating aquaculture pond system and growth pattern of aquatic organisms has gradually matured with the continuous development of aquaculture industry. Zhai and Zhang [1] established a plankton sub-ecosystem model of semi-intensive shrimp stocking pond in 1990s. Buonomo, Falcucci, Hull, and Rionero [2] built a dynamic ecological model of mixed cultivating pond for aquatic plants. Nunes and Parsons [3] simulated the ingestion and growth of *Litopenaeus stylirostris*.

Currently, shrimp aquaculture in China is evolving from traditional open low stocking density to closed high stocking density with infrequent or without replacement of water. However, high density closed stocking ecosystem with eutrophication deteriorates the stocking environment of shrimps. The ability of balancing organic load of this high density closed stocking ecosystem is the key to successful stocking. Artificial control measures such as feeding and aeration are of particular importance to high stocking density of shrimp. This study constructed a dynamic model of growth of shrimps using mathematical simulation based on the experimental data on field shrimp stocking to simulate and reflect the relationship among shrimp growth, pond ecosystem and artificial control to predict the potential risks and intervention of artificial control in macroscopic view in the production of shrimps in high density stocking pond.

Materials and Methods

Experimental Design

The field experiments were carried out in a high density shrimp pond with artificial aeration between May and September in Tanggu District (39° 1' 16" N, 117° 38' 49" E), Tianjin, China. Data of validation were obtained in the field. The area of the pond was 0.20 ha and the water depth was 3.0-3.5 m. Two 5 kW paddlewheel aerators were installed in the shrimp pond. Stocking water was high salinity brine mixed with underground fresh water, with a salinity of 13-25‰. Closed stocking mode was developed by adding water in draining water out in the stocking cycle. The shrimp fry of *Fenneropenaeus chinensis* were bought from Chengxin hatchery in Hangu District, Tianjin, China. The shrimp fry were stocked until 2.09 ± 0.31 cm in body length before transferring into separate cells with a stocking density of 250 ind/m^2.

In the early stocking stage, the main feed was fresh Artemia, supplemented with complete artificial feed. After shrimps growing to 5 cm in body length, pellet feed was fed to supplement at a frequency of 5-6 feedings per day. Of which daily feeding included two feedings of fresh food, 3-4 feedings of pellet feed every 4 hours. 0.6-1.2 kg Artemia per 10,000 shrimps and 0.2-0.3 kg pellet feed per 10,000 shrimps were provided. The whole stocking cycle was 75 days. Physical and chemical parameters of the pond were measured every 15 days during the experiment. Ten shrimps were selected randomly for the measurement of body length and weight. The production and survival rate of shrimp were calculated at the end of the experiment.

Conceptual Growth Model in the Pond Ecosystem

The shrimp stocking pond for the development of the growth modeling is a closed aquatic ecosystem under artificial control and manipulation (Fig. 1). The major interventions in shrimp stock include feeding, water change and mechanical aeration, etc. The artificial feed, formulated feed and Artemia, is the main energy source to support the growth of shrimps and zooplanktons, as well as the direct or indirect source of nutrients and detritus in the pond aquaculture. Mechanical aeration is the most important parameter in high density stocking of shrimps. It helps compensate internal oxygen debt of the pond aquaculture so as to maintain the concentration of dissolved oxygen for shrimp growth and ecological balance. Under high density stocking condition, shrimps become an absolute dominant species in the pond ecosystem. Shrimps consume artificial feed together with large amount of meiofauna and zooplanktons leading to a dramatic decline in the ingestible biomass within the pond ecosystem which would substantially weaken ecological functions of ecological unit. Moreover, in middle and late stages of shrimp stocking, high shrimp biomass produces large amount of excretes and shelling debris which becomes the main source of internal detritus in the ecosystem. In addition, shrimp excreted nitrogen in the process of growth gives rise to high load of nitrogen in the system. Phytoplaktons not only serve as food for zooplankton in water in where shrimps are stocking, but also plays an important role in improving the water quality in the shrimp pond [4]. While phytoplankton generates oxygen by photosynthesis to increase oxygen dissolved in pond water, it can absorb nitrogenous compounds such as NH_4^+ and NO_2^- that are harmful to shrimps. Zooplankton has an important function in the shrimp pond system. In early stage of shrimp stocking, zooplankton can be ingested by shrimps as food [5]. The ingestion of meiofauna by shrimps, mineralization, decomposition and release of nutrients deposited on the underwater interface form a complete stocking ecosystem with mutual benefit.

This conceptual model based on the dynamic model of growth of the shrimps in high density stocking pond was constructed using the ecological modeling software STELLA® 5.1.1 (High

Performance Systems, Inc., Hanover, New Hampshire, USA). The Euler's method was adopted for model integration. One day data were taken for mathematical simulation of shrimp growth.

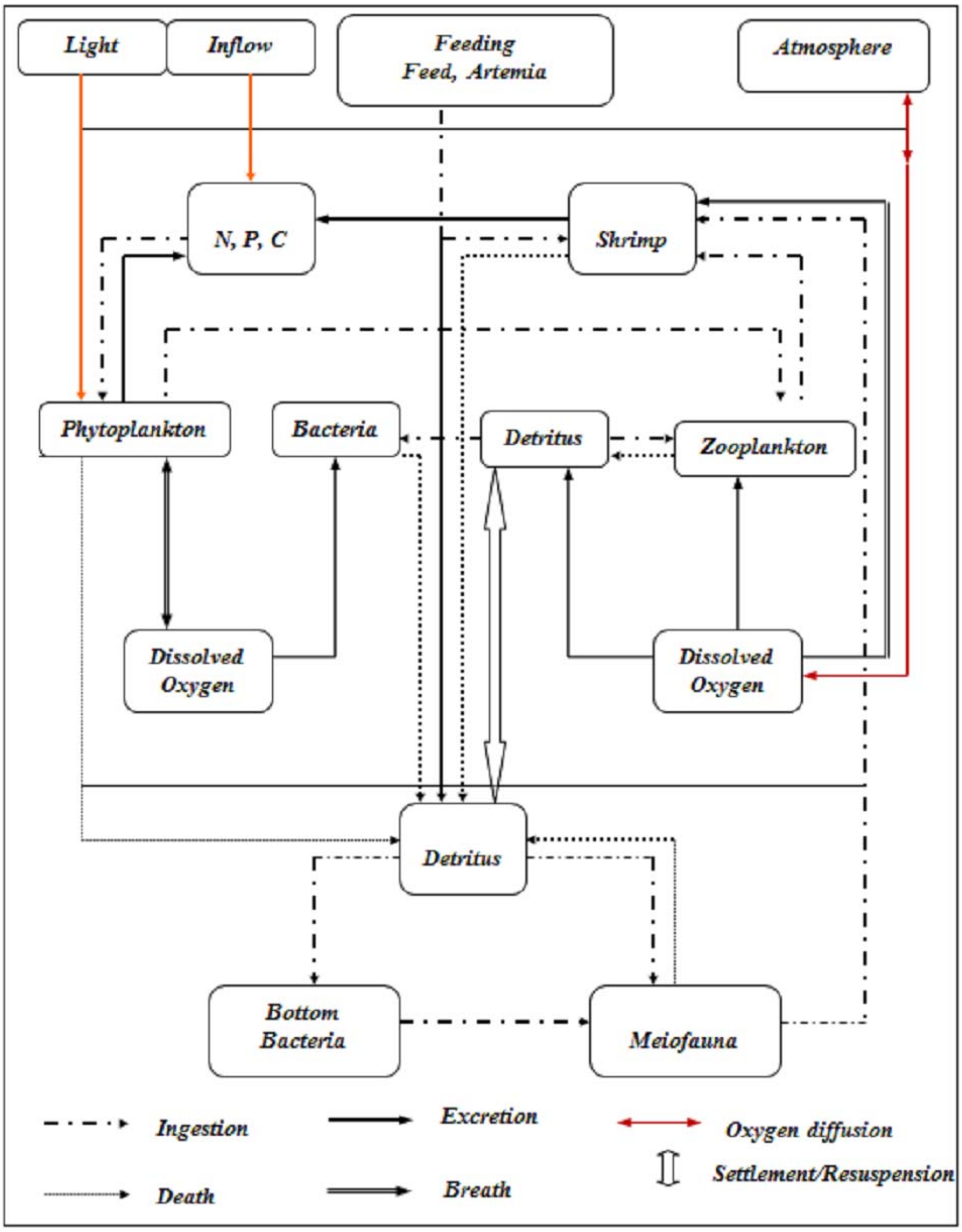

Figure 1. The sketch intensive shrimp (*Fenneropenaeus chinensis)* breeding ecosystem. N, nitrogen; P, phosphorus; and C, carbon

Model Structure

The Ecopath assumes zero energy balance between energy in and out in various functional groups of modeling subject [6], which is associated with the balance among shrimp growth, ingestion and metabolism. Shrimp growth is related to its individual weight, water temperature and the degree of solubility of oxygen in water [7, 8]. The equations of shrimp ingestion of carbon (Eq. 1) and the metabolism of carbon (Eq. 2) in this study were fit with the linear regression of indoor measured data by Zhang [7]. The shrimp growth equation and model diagram were shown in Fig. 2.

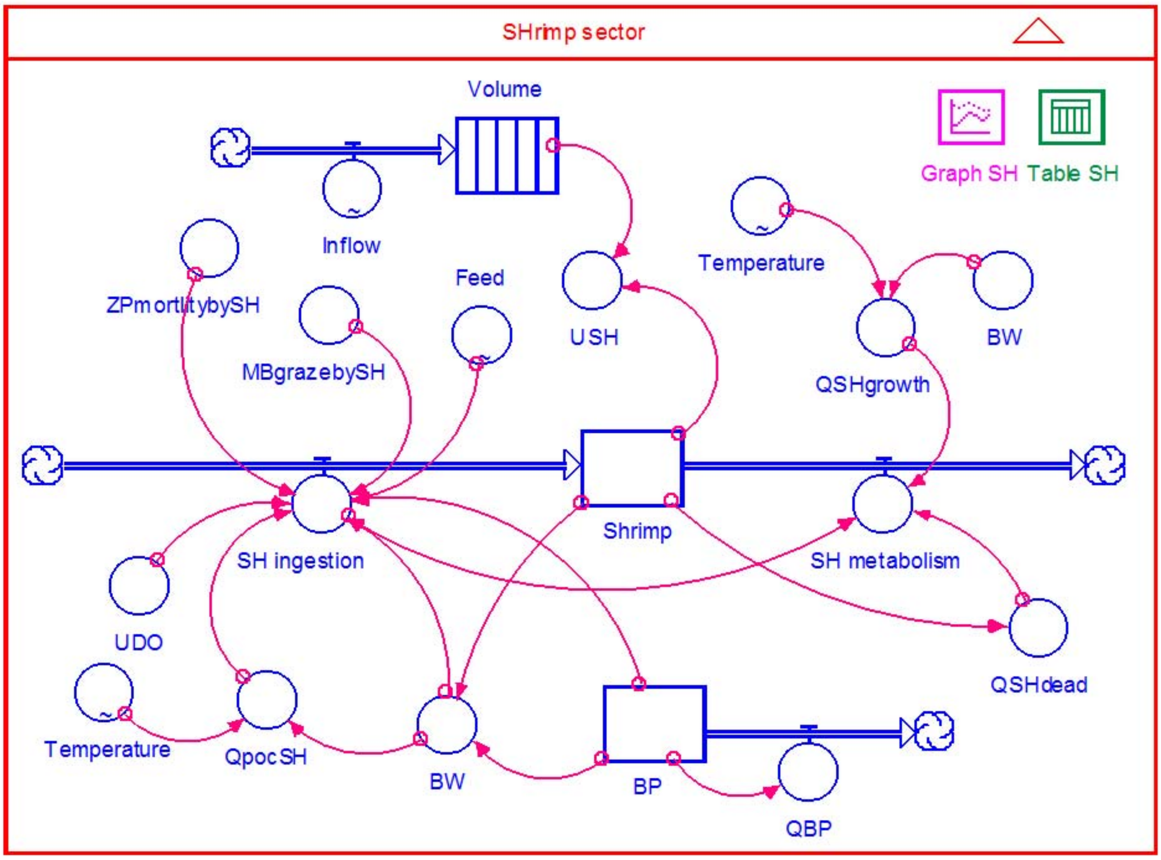

Figure 2. Model diagram of shrimp growth. BP, number if shrimps in the pond; BW. Wet weight of shrimpl; Feed, food feed; Flow, daily in folw; MBgrazebySH, ingestion of meiofauna by shrimp; QBP, nember of dead shrimps in the pond; QpocSH, ingestion C of *Fenneropenaeus chinensis*; QSHdead, dead number of shrimps in the pond; QSHgrowth, the ratio of growth C to ingestion C of *Fenneropenaeus chinensis*; SH ingestion, shrimp ingestion; SH metabolism, shrimp metabolism; UDO, unit water dissolved oxygen; Temperature water temperature; ZpmortlitybySH, ingestion of zooplankton by shrimp.

$$\frac{dShrimp}{dt} = SHingestion - SHmetabolism$$

$$SHingestion = MIN\left(\left(\begin{array}{l} QpocSH^{*} \times BP \times BW \times \lambda_1 \times \dfrac{UDO}{(UDO + KDO)} + MBgrazebySH^{**} \\ + ZPmortalitybySH^{***} \end{array}\right), \ Feed\right) \quad (1)$$

Where: QpocSH = Ingestion carbon (C) of Fenneropenaeus chinensis (mg C/g/day)
BP = Number of shrimps in the pond (ind/pond)
BW = Wet weight of shrimp (g)
λ1 = Growth promotion coefficient of Artemia (1/d)
UDO = Unit water dissolved oxygen (mg/L) [9]
KDO = 95 h semi-lethal dissolved oxygen (mg O_2/L)
MbgrazebySH = Ingestion of meiofauna by shrimp (mg C/pond)
ZpmortalitybySH = Ingestion of zooplankton by shrimp (mg C/pond)
Feed = Food feeding (mg C/pond), system forcing function.

$$* \ QpocSH = 3.2558 \times BW^{-0.365} \times e^{(0.076 \times Temperature)}$$

$$BP(t) = BP(t-dt) + (-QBP) \times dt = BP(t-dt) + (-INT(BP) \times \lambda_2) \times dt$$

$$BW = Shrimp / BP \times \lambda_3$$

Where: Temperature = water temperature (°C), system forcing function
QBP = Number of dead shrimps in the pond (ind/pond/day)
λ2 = Death rate of shrimps (%/d)
λ3 = Wet weight conversion coefficient of shrimp (g/mg C)

$$MBgrazebySH = \varepsilon_7 \times Shrimp \times \frac{UMB}{K_{UMB} + UMB}$$
**

Where: ε7 = Ingestion rate of meiofauna by the shrimps (mg C/mg C (Shrimp)/day)
UMB: Unit meiofauna (mg C/m^2), meiofauna/pond bottom area
KUMB = half-saturation density of ingestion of meiofauna by the shrimps (mg C/m^2)

*** $ZPmortalitybySH = \beta_2 \times Zooplankton \times SF$

Where: β2=Feeding rate of zooplankton by shrimps (1/day)
Zooplankton=Biomass of zooplankton in the pond (mg C/pond)
SF=Seasonal factor of feeding rate of zooplankton by the shrimps (%), system forcing function

$$SHmetabolism = (1 - QSHgrowth\,{*}) \times SHingestion + QSHdead\,{**} \tag{2}$$

Where: QSHgrowth=The ratio of growth C to ingestion C of Fenneropenaeus chinensis (%)
QSHdead = Dead number of shrimps in the pond (mg C/pond)

* $QSHgrowth = 2.6313 \times BW^{-0.182} \times e^{(-0.145 \times Temperature)} + 0.1745$

** $QSHdead = Shrimp \times \lambda_2$

Model Parameters

Appropriate selection of model parameters is crucial in building mathematical model [10]. The reliability of model parameters is critical to the rationality and accuracy of model results [11]. Basic parameters of the model can be selected and determined by looking up the literatures in suitable range. The parameters and the numerical values being used here were adopted from Zhang [7] (Table 1).

Table 1. Parameters and values for model construction

Parameter	Description	Value	Unit
KDO	95 h semi-lethal dissolved oxygen	0.9	mg O_2/L
†λ_1	Artemia growth promotion coefficient	1.8	1/d
λ_2	Death rate of shrimp	0.006	%/d
λ_3	Wet weight conversion coefficient of shrimp	110.91	g/mg C
ε_7	Ingestion rate of meiofauna by shrimp	0.33	mg C/mg C (Shrimp)/d
†K_{UMB}	Half-saturation density of ingestion of meiofauna by shrimp	90000	mg C/m^2
β_2	Feeding rate of zooplankton by shrimp	0.2	%/d

Note: "†" Parameter by calibration; O_2, oxygen; C, carbon (Adopted from Zhang [7])

Statistical Analysis

Results were presented as mean ± standard error of mean (SEM) evaluation. Differences among parameters were tested for statistical significance by analyzing the variance (ANOVA). Any difference was considered significant if $p < 0.05$.

Results and Discussion

The average body length and weight of the shrimps were 9.91 ± 0.65 cm and 8.59 ± 1.57 g, respectively. The daily growth rates of shrimps were 1.04 ± 0.19 mm in body length and 0.11 ± 0.08 g in body weight. The production of shrimp was 14.50 t/ha in the whole stocking cycle.

The growth variation of the shrimps was simulated from a stocking cycle of 90 days for modeling. The initial value was taken at the zeroth day. The simulated model was validated by the measured data on the growth of the shrimps on the field (Fig. 3). The data of simulation matched with the measured values ($p < 0.05$). The model successfully simulated the growth pattern of shrimps in a high density stocking pond. It also proved the satisfactory simulation of the growth process of shrimps on the field by the application of indoor energy balance equations (i and ii) from Zhang [9] in combination with the structure of pond ecosystem.

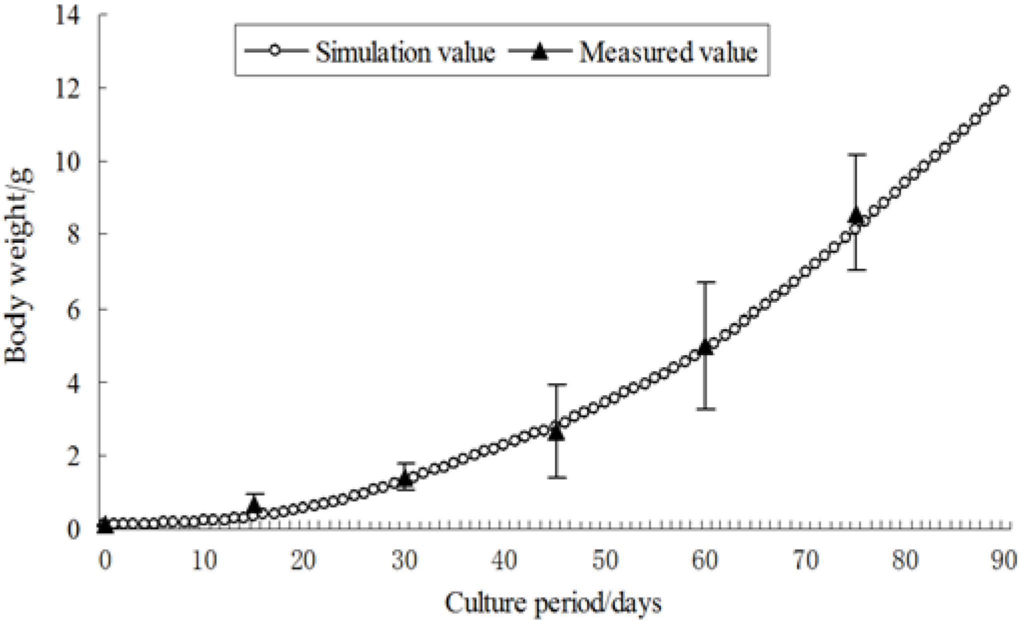

Figure 3. Simulation result of shrimp growth

In the early stocking stage, measured value was higher than the simulation value (0.68 g > 0.33 g, 15 d). This finding was attributed to higher feeding percentage of fresh Artemia in pond aquiculture leading to remarkable effect to growth promotion. It also indicated that feeding fresh Artemia supported the simulated growth of shrimps in early stage, and contributed a significant measure for enhancing aquatic production.

Sensitivity analysis has an important ecological significance of identifying the uncertainty in system analysis [12]. Single factor variation method was applied in the current study. The values of specific parameters were varied in accordance with the standard operating condition of the model. The mean value of a relative variation was taken with the state variables at various time points and then divided the relative change of that parameter to identify the sensitivity of the state variable [13]. The ranges of variation of parameters having been analyzed were based on the deviation of ±10% of the estimated range of the parameters [12]. The sensitivity analyses of key parameters of the model were then conducted (Table 2). The parameters with the sensitivity index exceeding ± 0.5 were defined as sensitive parameters, and those parameters with sensitivity index less than ± 0.5 were defined as insensitive parameters.

Table 2. Sensitivity analysis of key parameters1

Parameter	Description	Sensitivity index
KDO	95 h semi-lethal dissolved oxygen Artemia	-0.02，+0.02
λ_1	growth promotion coefficient	+0.08，-0.34
λ_2	Death rate of shrimps	+0.25，-0.25
Feed[2]	Frequency of artificial feeding	+0.67，-0.78
Temperature[2]	Water temperature	-0.65，+0.59

[1], Range of deviation was set as ±10%; [2], sensitive parameter

The single factor analysis of parameters illustrated that the growth of shrimps in high density stocking environment, artificial feeding and water temperature were sensitive parameters (Table 2). The findings suggest that the introduction and manipulation of artificial feeding has a direct impact on shrimp production in aquaculture. Optimal weight and production of shrimps cannot be achieved without sufficient feeding. High stocking density has been found to decrease the growth rate of the shrimps remarkably due to the crowding effect [14, 15]. Sandifer, Hopkins, Stokes, and Pruder [16] obtained a growth rate of 0.13 g/d in an experiment of stocking shrimp in an open high density shrimp pond. In a closed stocking experiment of *Penaeus monodon* [18], the growth rates of the shrimps under the stocking density of 25 ind/m^2 and 50 ind/m^2 were 0.11 g/d and 0.12 g/d, respectively. In the current study, the maximum stocking density of shrimps was 250 ind/m^2. The growth rates of the shrimps were 1.04 ± 0.19 mm/d in body length and 0.11 ± 0.08 g/d in body weight that aligned with Sandifer et al. [16] and Thakur and Lin [17].

The study was not conducted under favourable conditions regarding water quality and bottom substrate for optimal shrimp growth. The sensitivity analysis found that the main causes for influencing the growth rate of the shrimps were feeding fresh Artemia and at a frequency of 5-6 feedings per day. Moreover, high turbidity of water was resulted from the presence of large amount of pellet organisms, which was also a quantitative source of organic nutrients for the growth of the shrimps.

In the initial stage of the modeling, *Litopenaues vannamei* ingestion equation was adopted. It was found that the growth curve of the shrimps was tended to fit with the Logistic equation at 90th day simulation. However, the growth rate and the ingestion rate of the shrimps remarkably decreased with increasing body weight in the middle and late stocking stages when compared with the simulation of ingestion by *Fenneropenaeus chinensis*. Burford, Thompson, McIntosh, Bauman, and Pearson [18] used ^{15}N tracer agent to investigate the contribution of suspended matters in high density stocking ecosystem to the growth of *Litopenaeus vannamei.* The authors suggested that suspended particles in the stocking environment could steadily supply nutrients, particularly biological nitrogenous feed from suspended particles contributed to 18-29% of the growth of the shrimps [18]. Although there were no remarkable decreases in the growth rate and the ingestion rate in the late stocking stage, it was suggested *Fenneropenaeus chinensis* had a longer growth cycle than *Litopenaeus vannamei*. *Fenneropenaeus chinensis* is predicted to have greater production benefit with extended stocking cycle. Moreover, sensitivity analysis of water temperature in the current study indicated that shrimp metabolism increased with water temperature. Under the circumstance of the absence of additional feeding, there will be a decrease in the average weight of the shrimps. Cen, Hu, and Chen [19] have predicted the impact of water temperature on stocking *Litopenaeus vannamei* and constructed a mathematical model that provided scientific evidence of controlling water temperature for production and stocking management of *Litopenaeus vannamei*. Further research on the development of the simulation of the growth of different shrimp species using the ecological modeling is necessary to investigate the growth pattern of these species on high density pond.

Conclusions

The study demonstrated that the growth of *Fenneropenaeus Chinensis* was successfully simulated in a 90-day stocking circle in a high density pond. The measured value was higher than the simulation value (0.68 g > 0.33 g, 15 d). The handling and manipulation of the artificial feeding at different water temperature have direct impact on the growth and production of the *Fenneropenaeus Chinensis*. Further investigation is necessary to understand the growth and production factors on other *Fenneropenaeus* species.

Acknowledgements

This study was supported by the grants from the Key Lab Foundation of Zhuhai (R1053) and the Key Innovative & Demonstrate Base Program of Guangdong of China (2013B090300009, 2016A020227016).

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