Optimization of feed management for Pacific White shrimp (*Litopenaeus vannamei*)

By

To Pham Thi Ha Van

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 08, 2016

Keywords: Pacific white shrimp, feed management, feed ration, growth performance, feed cost, economic return

Approved by

Donald A. Davis, Chair, Professor of School of Fisheries, Aquaculture, and Aquatic Sciences
William H. Daniels, Associate Professor of School of Fisheries, Aquaculture, and Aquatic Sciences
James Stoeckel, Associate Professor of School of Fisheries, Aquaculture, and Aquatic Sciences

Abstract

Manufactured feed is one of the important components of commercial shrimp aquaculture, providing nutritional balance for farmed shrimp. However, it is also the primary source causing problems related to water quality. Although feed cost represents a large portion of variable costs in shrimp farming, profoundly influencing the profitability of farm operation, feed use is projected to continue to increase due to rapid expansion of farm intensification. Natural food productivity plays a subordinate role in high density ponds. However, it is still important in providing essential nutrients for shrimp in semi-intensive farms, especially at early stages, and potentially helps to reduce the use of commercial feed if exploited effectively. Adoption of good feed management allows cultured animals to attain nutritional needs from both commercial feed and natural productivity efficiently, improving feed efficiency and reducing wastes derived from commercial feed. Different feeding protocols were evaluated to estimate the effects of feeding rates on growth, FCR and economic returns of *L.vannamei* shrimp raised in ponds and outdoor tanks. In the first experiment, three feeding protocols were evaluated, including standard feeding protocol (SFP), 10% reduction in the SFP (SFP:90), and 10% increase in the SFP (SFP:110). Shrimp were stocked at a density of 10 shrimp/m^2 and harvested after 17 weeks. The results showed that increasing feed by 10% from standard feed ration showed insignificant improvement in mean growth and economic performance. On the other hand, no significant reduction in mean production, survival, FCR and partial return were found for shrimp receiving 10% less feed than typical ration.

In the second experiment, 35 shrimp/m^2 were stocked into 24 outdoor tanks that were managed to mimic pond conditions. Six feeding protocols providing a range of feed inputs based on the SFP for tanks (T) were evaluated over six weeks. The results revealed that increasing feed input (T100:110 and T110) did not improve mean growth and FCR, but led to an increase in feed cost per unit of shrimp production. Contrarily, an insignificant reduction in mean growth and survival of shrimp fed with phased feeding protocol (T80:90:100) reduced significantly feed cost per kg shrimp produced, indicating the cost efficiency. Standard feeding protocol (T100) appeared to produce bigger shrimp compared to restricted feeding protocols (T80:90:100, T90 and T90:100), although no significant differences were found except for T90.

The third experiment was conducted in twelve ponds with shrimp stocked at a density of 28 shrimp/m^2. Three feeding protocols included standard feeding protocol (SFP), 10% reduction in the SFP (SFP:90), and phased feeding protocol (SFP:80:90:100) in which the feed input was changed at 4-wk intervals starting at 80% during weeks 4-8, 90% weeks 9-12, and 100% weeks 13-16. The results indicated no significant effects on mean growth performance of shrimp restricted to 10% feed input (SFP:90 and SFP:80:90:100). Feed cost was greater for SFP but feed cost per production unit was similar in all treatment. Overall, the findings in these studies demonstrated that increasing the feed ration did not improve growth performance nor economic returns of shrimp raised in ponds conditions. Selection of restricted or full feeding ration depends on the financial status and outcome expectancy of each farm. Feed restriction seems to be more favorable for operations preferring lower investment feed; meanwhile, appropriately practicing standard feeding protocol is encouraged in order to produce shrimp cost-effectively.

Acknowledgements

Behind a work is teamwork because a valuable achievement is never accomplished alone. I would like to acknowledge the following exceptional individuals during the course of my research and education in Auburn. My sincere appreciation goes to Professor Donald A. Davis. My sense of science was very underdeveloped before joining his lab. Thank you for giving me an opportunity to gain comprehensive understandings of what scientific research looks like and thanks for instructive comments that have changed me on such a deep level that I do not even have the proper words to describe my appreciation. This thesis is made possible by your continued instruction and many hours editing to ensure the methodology was clearly explained and the concepts well communicated. Dr. William Daniels, it is hard for me to express my feelings and thanks for all things you have done to help me with transition to graduate school. Sometimes, I feel like I bothered you, but you always calmed my fears no matter how worried I was. I am grateful for the extra work that you have contributed to this thesis. Your feedback, suggestions and attention to every detail are absolutely precious. Dr. Jim Stoeckel, thank you so much for your service that helped me to finish this work. I appreciate immensely your wisdom, keen insights and willingness to help out whenever needed. Nobody, including me, can fail to admire your calm and patience. Dr. Guillaume Salze, your knowledge and persistence are so inspirational. More importantly, thank you for always making yourself available to answer my questions and give advice. Ms. Melanie Rhodes, I am privileged to work with such a dedicated person like you. I admire your experience and commitment towards your jobs. Dr. Donald

Jackson, many thanks for inspiring me to go farther. Your kindness, faith-filled stories and words of encouragement have had such a powerful influence on me that you will not believe. It is you who originally showed me that there is nothing wrong with dreaming big dreams. It was a great honor for me to have been acquainted and worked with the extraordinary individuals of Dr. Davis' nutrition lab: Yangen Zhou, Sirirat Chatvijikul, Lay Nguyen, Xuan Qiu, Karima EI Naggar, Mingming Duan, Charles Roe, Romi Novriadi, Thomas Derbes, Igor Simone Tiagua Vicente, and Shelby Oliver. May Myat Noe Lwin, thank you for sound advice and the special bond we share. Your vibrant personality always put a can-do attitude on my face. I am enormously blessed with people like you. Last but not least (many people to list, but you know where you are in my heart), heartfelt thanks to Gina Zubert and your family whose unyielding love and unconditional aid encouraged me onward. I greatly appreciate you for always reaching out to me with helping hands and willingness to put your life on pause to listen to my concerns when I was down. I think of you as a big sister and feel that we are both learning a lot about life.

Table of contents

List of tables

CHAPTER II

CHAPTER III

List of figures

CHAPTER II

CHAPTER III

CHAPTER I
INTRODUCTION

Aquaculture plays an important role in meeting increasing demand of food consumption and reducing pressure of nutrient need due to expansion of human population. FAO (2014) reported that it contributed 42.2% to the world total food fish production in 2012. Among aquaculture species, crustaceans accounted for a significant component in the growth of aquaculture, contributing about 9.7% (6.4 million tonnes) in global food and sharing 22.4% in value (US $30.9 billion) in 2012 (FAO, 2014). Farming of Pacific white shrimp (*Litopenaeus vannamei*) has become more attractive with culturists due to advantageous characteristics of this species, such as fast growth, low salinity tolerance, low risk of disease, and lower protein requirement compared to the second largest farmed black tiger shrimp (*Penaeus monodon*). Expansion of shrimp farms has been primarily in Asia (China, Thailand, Indonesia and Vietnam) and Latin America (Ecuador, Mexico and Brazil). Prein (2007) noted that increase in shrimp aquaculture production was primarily achieved by intensification of farming systems, which was often characterized by increasing material input (feed mainly). Semi-intensive and intensive shrimp farming heavily relies on commercial feed as a major source of nutrition, causing pressures on economic, environmental and social matters. Economically, feed cost normally accounts for 40-60% of the total production cost in shrimp culture (Chanratchakool et al., 1994; Lovell, 1998; Hertrampf and Piedal-Pascual, 2000). This large component of variable costs substantially influences the profitability of the farm operation. From an environmental standpoint, formulated feeds are the original source of nutrients. Hence, they are the first factor responsible for nutrient loads that can deteriorate water quality and the pond bottom due to uneaten feed and animal excretion (Burford and Williams, 2001; Avnimelech and Ritvo, 2003).

From the perspective of sustainability, although the contribution of aquaculture sector to global food supply is much smaller than that of poultry and bovine sectors, it consumes 68% of the total global fishmeal production and 74% of the total global fish oil production in 2012 (Mallison, 2013). The increasing demand of fishmeal and fish oil encourages over exploitation of wild fish, which has an important function in oceanic food chains (Deutsch et al., 2007).

De Silva (1989) noted that reducing feed costs in semi-intensive aquaculture systems in the tropics could be achieved by focusing on determining the optimal protein requirement of cultured animals and employing different feeding strategies. Being identified as the most expensive component in feed cost, considerable research has concentrated on reducing the cost per unit of protein by using alternative protein resources (Lim and Dominy, 1990; Guillaume, 1997; Roy et al., 2009; Sookying and Davis, 2011). Conversely, despite the potential to save cost and reduce environmental pressures, very little attention has been paid to feed management practices (Carvalho and Nunes, 2006).

Feed management has been identified as an important factor influencing aquaculture production economics (Jolly and Clonts, 1993) and water quality (Jory, 1995; Boyd and Tucker, 1998). In farming models that rely on external feed input as the main nutrient source, feed is the main source of pollution for fish farms (Roqued’Orbcastel et al., 2009). Inefficient use of feed greatly affects profitability of farm and culture water. Nitrogen (N) and phosphorous (P) are the two main components causing water pollution when the concentrations of these elements exceed the processing capacity of the water body. Adoption of good feed management is effective in reducing water quality problems and promotes success of shrimp production. Seymour and Bergheim (1991) believed that the most effective way to reduce feed waste from aquaculture farms was presenting feed when the animal could use it most efficiently or minimizing the feed loss caused by overfeeding. Kaushik (2000) assumed that while underfeeding might restrict the maximum growth of cultured animals, overfeeding was likely to cause increasing pollution resulting in increased cost for water quality management. Typically, around 30% of the nutrient input is assimilated and retained in the harvested biomass; whereas, the remainder adds to the nutrient load of the culture system (Thakur and Lin, 2003; Davis et al., 2006) and must be processed by the culture system.

Adding formulated feed is one of the main characteristics of semi-intensively and intensively managed shrimp ponds to provide nutritional needs of vitamins, minerals and other micronutrients that are progressively scarce during the progression of the culture cycle (Gamboa-Delgado, 2013). However, application of artificial feeds should not exceed the maximum processing capacity of culture system and one should consider the presence of potential natural food to avoid unnecessary feed input. The contribution of natural foods as a nutrient source is well documented (Tiews et al., 1976; Cockcroft and Mclachlan, 1986; Smith et al., 1992). Phytoplankton and zooplankton are the most common food voluntarily selected by shrimp in the early stage; about 30% of the increase in shrimp biomass is obtained from natural productivity (Schroeder, 1983; Anderson et al., 1987; Parker et al., 1989; Gamboa-Delgado, 2003). The primary goal of feed management strategies should be to optimize the feed inputs and the use of nutrients, to improve feed conversion ratios, and reduce the potential environmental effects on culture system and waste water (Jory, 2001).

Apart from satisfying nutrient requirements, feed inputs should be managed to avoid unnecessary costs, water pollution and adapted to the feeding habit of the animal. Despite the importance, information pertaining to feed management is not well investigated. The goal of this study was to improve current feed management strategies for the culture of *L. vannamei* under semi-intensive pond conditions. The objective of the current thesis was to estimate the effects of feeding rates on production, FCR and economic returns of semi-intensive production of Pacific white shrimp *L. vannamei* reared in outdoor ponds and green water tanks. A summary of specific objectives is presented below.

1. Evaluate the effects of three feeding rations when shrimp are stocked in ponds at a density of 10 shrimp/m^2.
2. Evaluate the effects of different feeding rations when shrimp are stocked in outdoor green water tanks at a density of 35 shrimp/m^2.
3. Evaluate the effects of feed inputs when shrimp are stocked in ponds at a density of 28 shrimp/m^2.

References

Anderson, R. K., Parker, P.L., Lawrence, A., 1987. A $^{13}C/^{12}C$ trace study of utilization of presented feed by a commercially important shrimp *Penaeus vannamei* in a pond grow-out systems. Journal of the World Aquaculture Society 18, 148-155.

Avnimelech, Y., Ritvo, G., 2003. Shrimp and fish pond soils: processes and management. Aquaculture 220, 549-567.

Boyd, C.E., Tucker C.S., 1998. Pond aquaculture water quality management. Kluwer Academics Publisher, Boston, Massachusetts, USA.

Burford, M.A., Williams, K.C., 2001. The fate of nitrogenous waste from shrimp feeding. Aquaculture 198, 79-93.

Carvalho, E.A., Nunes, A.J.P., 2006. Effects of feeding frequency on feed leaching loss and grow-out patterns of the white shrimp *Litopenaeus vannamei* fed under a diurnal feeding regime in pond enclosures. Aquaculture 252, 494-502.

Charatchakool, P., Turnbull, J.F., Funge-Smith, S., Limsuwan, C., 1994. Health management in shrimp ponds. Aquatic animal health research institute. Department of Fisheries. Kasetsart University, Bangkok, Thailand.

Cockcroft, A., Mclachlan, A., 1986. Food and feeding habits of the surf zone penaeid Prawn *Macropetasma africanus* (Balss). Marine Ecology 7, 345-357.

Davis, D.A., Amaya, E., Venero, J., Zelaya, O., Rouse, D.B., 2006. A case study on feed management to improve production and economic returns for the semi-intensive pond production of *Litopenaeus vannamei*. Pages 282-303 in: Cruz Suarez, L.E., Maria, D.R., Salazar, M.T., Lopez, M.G.N., Cavazos, D.A.V., Cruz, A.C.P., Ortega A.G. (Eds.), Avances en Nutriciónacuícola, VIII. Simposio Internacional de Nutrición Acuícola. [Advances in aquaculture nutrition, VIII. International Symposium on Aquaculture Nutrition.] Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, Mexico.

De Silva, S.S., 1989. Reducing feed costs in semi-intensive aquaculture system in the tropics. Naga, The ICLARM Quarterly 12, 6-7.

Deutsch, A., Graslund, S., Folke, C., Troell, M., Huitric, M., Kautsky, N., Lebel, L., 2007. Feeding aquaculture growth through globalization. Exploitation of marine ecosystems for fishmeal. Global Environmental Change 17, 238-249.

Gamboa-delgado, J., 2013. Nutritional role of natural productivity and formulated feed in semi-intensive shrimp farming as indicated by natural stable isotopes. Aquaculture 6: 36-47.

Gamboa-Delgado, J., Molina-Poveda, C., Cahu, C., 2003. Digestive enzyme activity and food ingesta in juvenile shrimp *Litopenaeus vannamei* (Boone 1931) as a function of body weight. Aquaculture Research 34, 1403-1411.

Guillaume, J., 1997. Protein and amino acids. D'Abramo L.R., Conklin, D.E., Akiyama, D.M. (Eds.), Crustacean Nutrition, Advance. World Aquaculture Vol. 6, World Aquaculture Society, Baton Rouge, LA, USA, pp. 26-50.

Hertrampf, J.W., Piedal-Pascual, F., 2000. Handbook on Ingredients for Aquaculture Feeds. Kluwer Academic Publishers, Dordrecht, The Netherlands. 573 pp.

Jolly, C.M., Clonts, H.A., 1993. Economics of Aquaculture. Food Products Press (The Haworth Press), Binghamton, New York, USA.

Jory, D.E., 1995. Feed management practices for a healthy pond environment. Pages 118-143 in: Browdy, C.L., Hopkins, J.S. (Eds), Swimming through troubled water, proceedings of the special session on shrimp farming. World Aquaculture Society, Baton Rouge, LA, USA.

Jory, D.E., Cabrera, T.R., Dugger, D.M, Fegan, D., Lee, P.G., Lawrence, A.L., Jackson, C.J., McIntosh, R.P., Castaneda, J., 2001. Perspectives on the application of closed shrimp culture systems. Pages 104-152 in: Browdy, C.L., Jory, D.E. (Eds.), The New Wave, Proceedings of the special session on sustainable Shrimp culture, Aquaculture. 2001. The World Aquaculture Society, Baton Rouge, Louisiana Orlando, USA.

Kaushik, S.J., 2000. Feeding allowance and feeding practices. In: Basurco, B. (Ed.), Recent advances in Mediterranean aquaculture finfish species diversification. Proceedings of the Seminar of the CIHEAM Network on Technology of Aquaculture in the Mediterranean (TECAM). Cahiers Options Mediterranean 47, 53-59.

Lim, C., Dominy, W., 1990. Evaluation of soybean meal as a replacement for marine animal protein in diets for shrimp (*Penaeu svannamei*). Aquaculture 87, 53-63.

Lovell, T., 1998. Nutrition and Feeding of Fish. Kluwer Academic Publishers, Norwell, Massachusetts.

Parker, P.L., Anderson, R. K., Lawrence, A., 1989. A $\delta^{13}C$ and $\delta^{15}N$ tracer study of nutrition in Aquaculture: *Penaeus vannamei* in a pond grow-out system. In: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), Stable Isotopes in Ecological Research. Springer-Verlag, New York, pp. 288-303.

Prein, M., 2007. Comparative analysis of material flows in low input carp and poultry farming: an overview of concepts and methodology. In: Bartley, D.M., Brugere, C., Soto, D., Gerber, P., Harvey, B (Eds.), Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO Fisheries Proceedings. No. 10. Rome. pp. 183-199.

Rana, K.J., Siriwardena, S., Hasan, M.R., 2009. Impact of rising feed ingredient prices on aquafeeds and aquaculture production. FAO. Fisheries and Aquaculture Technical Paper. No. 541. Rome, FAO. 2009. 63p.

Roqued'Orbcastel, E., Blancheton, J.P, Aubin, J., 2009. Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. Aquaculture Engineering 40, 113-119.

Roy, A.L., Bordinhon, A., Sookying, D., Davis, D.A., Brown, T.W., Whitis, G.N., 2009. Demonstration of alternative feeds for the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters of west Alabama. Aquaculture Research 40, 490-503.

Seymour, E.A., Bergheim, A., 1991. Towards a reduction of pollution from intensive aquaculture with reference to the farming of salmonids in Norway. Aquaculture Engineering 10, 73-88.

Smith, D.M., Dall, W., Moore, L.E., 1992. The natural food of some Australian penacids. In: Allan, G.L., Dall, W. (Eds.), Proceeding. Aquaculture Nutrition Workshop, 15-19 April 1991, Salamander Bay, Australia. NSW Fisheries Brackish Water Fish Culture Research Station, Salamander Bay, Australia, pp. 95-96.

Sookying, D., Davis, D.A., 2011. Use of soy protein concentrate in practical diets for Pacific white shrimp (*Litopenaeus vannamei*) reared under field conditions. Aquaculture 319, 141-149.

Thakur, D.P., Lin, C.K., 2003. Water quality and nutrient budget in closed shrimp (*Penaeus monodon*) culture systems. Aquaculture Engineering 27, 159-176.

Tacon, A.G.J., Hasan, M.R., Metian, M., 2011. Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. FAO Fisheries and Aquaculture Technical Paper No. 564, p. 87.

Tiews, K., Bravo, S.A., Ronquillo, I.A., 1976. On the food and feeding habits of some Philippine shrimps in Manila Bay and San Miguel Bay. Philip. J. Fisher. 14, 204-213.

CHAPTER II

EVALUATION OF THREE FEEDING RATES FOR PACIFIC WHITE SHRIMP *Litopenaeus vannamei* REARED AT LOW DENSITY IN PONDS

Abstract

Feed cost is generally the largest component of variable costs in semi-intensive and intensive farming. Proper feed management is an approach that reduces overall production costs and promotes reduced environmental impacts. Given the potential benefits of optimizing feed management, this research was conducted to investigate further modifications of a standardized feed management strategy and the effects on production and economic return. Growth performance of *Litopenaeus vannamei* was evaluated in production ponds stocked at 10 shrimp/m^2 (9 production ponds, three feeding schedules - three replicates). The treatments were designed based on a standard feeding protocol (SFP, control), which was either increased or decreased by 10% (SFP:110 and SFP:90). After 17 weeks of culture, no significant differences in mean survival (63.9% - 67.1% and FCR (0.84 - 1.20) were observed. The yield for shrimp offered the SFP (2476 kg/ha) was significantly higher than that of SFP:110 (1707 kg/ha). Reducing feed input by 10% reduced the feed cost. However, the average weight of shrimp fed with SFP:90 (30.7 g) was not as big as shrimp fed with SFP (35.3 g), thereby reducing the economic value from $8479/ha (SFP) to $6459/ha (SFP:90). Similarly, increasing feed inputs did not significantly increase production and thus did not improve economic returns. Based on the observed results, the standard feeding protocol, which was based on historical performance for this site, was appropriate while increasing or decreasing feed inputs did not improve economic returns from the feed.

1. Introduction

Moving from extensive to semi-intensive shrimp aquaculture is not only a matter of increasing stocking density but also proper management of water quality and feeding. The growth and survival of shrimp depend on numerous factors such as the living habitat, water quality and nutrition. From a nutritional standpoint, the use of complete feeds is a must to compensate for quantitative and/or qualitative insufficiencies of natural food. This also results in increase in operating costs which must be optimized. As feed cost is generally the largest component of variable costs in semi-intensively and intensively managed shrimp ponds, there is a trend towards searching for cheaper plant-based ingredient or reducing the inclusion of the most expensive feed stuffs such as fish meal, vitamin and minerals in feed formulation has occurred (Piedad-Pascual et al., 1990; Trino et al., 1992; Tidwell et al., 1993; Davis and Arnold, 2000; Davis et al., 2004; Roy et al., 2009; Sooking et al., 2011). Although nutritional balance in feed is essential and determines the growth performance of the cultured animal, optimal economic efficiency can be attained only when feed is properly offered. Feed management strategies in aquaculture address major concerns of the culturist because it regulates the ration size, feeding frequency and the distribution of feed to meet the nutritional requirements of the animal. In addition to impacting key performance indicators, such as growth rate and FCR, each of these components can also profoundly influence the culture habitat and environment (Talbot et al., 1999; White, 2013).

Roqued'Orbcastel et al. (2009) emphasized that feed was the initial source of waste entering the culture system either directly as uneaten feed or as physiological waste from the culture animal. These wastes have a direct effect on the aquaculture environment. Poor feed quality and poor feeding strategy degrade the culture environment. Excess nutrients not utilized by farm animals are released into the environment and have to be assimilated or they accumulate. Only a small proportion of the feed supplied to the culture system is taken up in the culture species (Thakur and Lin, 2003; Davis et al., 2006; White, 2013). The rapid development of more intensive culture systems in some countries has resulted in higher stocking densities and higher feed inputs. Quite often this is associated with higher FCR. Cole and Boyd (1986) documented that the increased feeding rates surpassed the natural carrying capacity in ponds which could deteriorate water quality. Such failures in shrimp production are often blamed on feed quality, water quality, post-larvae quality, and/or disease, although the origin of the problem in most cases is caused by poor feed management (Piadad-Pascual, 1993).

Feeding schemes need to be based on efficient delivery of nutrients and feeding habits of growth stages. In the larval and post-larval culture phases of shrimp, for example, results of some experiments showed that animals obtained significantly higher amounts of dietary carbon from live prey (Artemia and rotifers) than from formulated feed (Gamboa-Delgado and Le Vay 2009). Although the contribution of natural productivity to satisfy nutritional needs decreases as the shrimp biomass increases, the presence of naturally occurring food organisms is still important in pond culture (Anderson et al., 1987; Parker et al., 1989; Reymond and Lagardere, 1990; Moriarty, 1997; Focken et al., 1998; Gamboa-delgado, 2013). In a 9-week-experiment, shrimp (initial mean size of 6.34 g) were reared in flow-through system allowing shrimp to access the natural food from ponds, Roy et al. (2012) documented that shrimp receiving 60% and 80% amount of standard feed input had similar weight gain and final weight with shrimp getting standard feed ration.

With the increasing trend in intensification of shrimp farming, feed quality and feed quantity are the keys factors affecting the viability of this culture model. While the former has received a great deal of attention and is intensively studied, the latter is not fully investigated. The basal feed management strategy used in the present study have been pieced together based on previous studies and general improvement at the facility over the years (Zelaya, 2005; Davis et al., 2006; Venero et al., 2007; Sookying et al., 2011; Achupallas et al., 2015). The standard feed management has been found to produce good results at a range of densities: 17, 26, 35, and 45 shrimp/m^2 (Sookying et al., 2011) but has not been systematically validated. Therefore, the objective of this study was to determine the effects of varying feeding rates on mean final weight, production, FCR and economic returns of Pacific white shrimp *Litopenaeus vannamei* reared in ponds at a density of 10 shrimp/m^2.

2. Materials and Methods

The production trial was conducted at the Alabama Department of Conservation and Natural Resources, Marine Resources Division, Claude Peteet Mariculture Center in Gulf Shores, Alabama. For this work, Pacific white shrimp *L. vannamei* post-larvae (1.3 mg mean initial weight) were obtained from Shrimp Improvement Systems, Islamorada, Florida, and nursed for 23 days prior to stocking into production ponds. The details of pond structures and the procedure of pond preparation (including tilling ponds, filling with brackish water, and fertilization) are described by Sookying and Davis (2011). The 17-week production trial was conducted in nine 0.1-ha ponds at an initial stocking density of 10 shrimp/m^2 (119 mg mean weight). Three feeding protocols were evaluated starting at week four and continuing until the end of the production trial.

Feed management

Throughout the production trial, feed was offered twice daily (0800 h and 1600 h). Feeding rates in the pond during the 1st, 2nd, 3rd and 4th weeks were 3, 6, 10, and 15 kg of feed/ha/d, respectively. After four weeks (28 days) of pond culture the shrimp were fed based on the assigned feed treatments. A sinking 3.2 mm-extruded commercial feed (40% crude protein (CP), 8% lipid) was offered until the 6th week; thereafter, a second commercial feed (35% CP, 8% lipid) was provided until harvest. Feeds were commercially manufactured by Rangen Inc. (Angleton, Texas).

The standard feeding protocol (SFP) has been used at this site for many years with good success and is based on accumulated data over the years. The protocol is based upon a few assumptions of growth, survival, and FCR. Daily rations are calculated based upon an expected weight gain of 1.3 g/week, an estimated FCR of 1.2, and a final survival rate of 75% (mortality rate of 1.47% weekly). To evaluate the potential of reducing or increasing feed inputs from the standard feeding protocol, the quantity of feed was either increased or decreased by 10% to produce the three treatments (SFP:110, SFP, and SFP:90). Actual weekly feed inputs per ha are presented in Figure 1.

Water quality monitor and harvest

Temperature, salinity, dissolved oxygen (DO) and pH were monitored three times daily at sunrise (0500-0530 h), during the afternoon (1400-1430 h), and at night (2000-2030 h) using a DO meter (YSI ProPlusQuatro meter, Yellow Spring Instrument Co., Yellow Springs, Ohio). All ponds were provided supplemental aeration using a 1- or 2-hp aerator depending on available equipment (1-hp Aquarian™, Air-O-Lator, Kansas City, Missouri, or 1-hp or 2-hp Aire-O_2, Aeration Industries International Inc., Minneapolis, Minnesota) to try to maintain DO above 3 mg/L. This trial was conducted with minimal water additions, primarily to make up for water loss by evaporation. Secchi disk readings and total ammonia-nitrogen (TAN) were monitored once per week. Water samples in all ponds were taken at the depth of 30-50 cm, and then TAN was measured using an Orion ammonia electrode probe (Thermo Fisher Scientific Inc., Waltham, Massachusetts). Shrimp sampling was conducted weekly using two 5-foot cast nets (monofilament net, 1.22 m radius and 0.95 cm opening). Approximately 60 shrimp in each pond were collected to determine the average weight and visually check the health of shrimp.

The shrimp were harvested at the end of the 17-wk culture period. Harvesting was carried out over a three-day period with feed being withdrawn 24 hours prior to harvest. In anticipation of harvesting, approximately two thirds of the water was discharged from the pond and an aerator was placed above the catch basin to ensure adequate DO levels. On the harvest day, the aerator was removed, the remaining water was drained and the shrimp were pumped from the catch basin with a fish pump (Aqualife- Life pump, Magic Valley Heli-arc and Mfg, Twin falls, Idaho) equipped with 25-cm diameter suction pipe, dewatered and transferred to a truck. The shrimp were then rinsed and weighed, and then approximately 150 shrimp from each pond were randomly sampled to determine individual weights. Mean final weight, final yield, FCR, survival and size distribution were determined.

Economic analysis

In order to assess the partial return, economic analysis was carried out based on feed input being responsible for the major production cost. Calculations were similar to those used by Sookying et al. (2011). Production value (USD/ha) was calculated based on the quantity of shrimp (head on, shell on) for farm gate prices for each size class. Farm gate price of shrimp varied greatly, depending on size and local market. In this study, 2.4-4.4 USD/kg were applied for shrimp sizes from 33-155 count (shrimp/kg). The costs used for size groups in this study were detailed in Table 1. Partial returns were determined by subtracting feed cost (1.08 USD/kg used in this study) from production value.

Statistical analyses

Statistical analyses were conducted using SAS 9.4 (SAS Institute, Cary, North Carolina). Data were analyzed using one-way analysis of variance to determine significant differences ($P < 0.1$) existed among treatments. When significant differences were observed, the Student-Neuman-Keuls multiple range test was used to determine differences among treatments.

3. Results

In general, water quality parameters were typical for this site. The observed water quality was appropriate to support good growth and survival of *L. vannamei* over the 17-wk period (Table 2). High mortality rates were observed in two ponds (SFP and SFP:90) after stocking (observable number of weak or dead PL's at the pond bank) and subsequent samplings indicated poor survival after stocking. At harvest, the poor survival in these ponds was confirmed and attributed to low survival at stocking, presumably due to water quality problems in the transfer tanks. Consequently, these ponds were excluded from the study.

At the end of pond trial, final mean weights of the shrimp ranged from 27.2 to 35.3 g, final yield varied from 1707 to 2476 kg/ha, survival ranged between 63.9% and 67.1%, and FCR varied from 0.84 to 1.20. The largest mean weight (35.3 g) was seen in SFP and the smallest individual mean weight was observed in the SFP:110 (27.2 g). FCR was highest in SFP:110 (1.2), followed by SFP:90 (0.92) and SFP (0.84), although these differences were not statistically significant. Significant differences in yields were observed, with the SFP producing the highest yield (Table 3).

As would be expected, the three feed inputs resulted in significant differences in feed cost which ranged from 2001 to 2425 USD/ha. Partial return ranged from 8479 to 5671 USD/ha for

SFP and SFP:110, respectively (Table 3). No significant differences were observed in mean feed cost per kg of shrimp produced and partial returns among these treatments.

4. Discussion

Improving feed management should be a goal of all farms because of the potential of improving economic performance. Proper application of feed management should include 1) the utilization of high quality feed (e.g. balanced nutrition, nutrient density, digestibility, and palatability etc.), 2) suitable application of the feed with upper limits designed to reduce adverse effects on the environment (i.e. avoiding overfeeding), 3) links to improve economic returns of the farm (reduce the feed cost for producing each unit of shrimp) (Davis et al., 2006). Proper feed management is not an easy task and is poorly understood because many factors affect growth and survival. Overfeeding is very common in many farms and research settings worldwide, typically hoping it would accelerate shrimp growth (Martinez-Cordova et al., 1998). This practice has been documented to be inefficient to improve growth and quite often causes adverse effects on aquatic organisms due to deterioration of pond bottom quality and water quality (Hopkins et al., 1991).

The standard feed management has been found to produce good results at a range of densities: 17, 26, 35, and 45 shrimp/m^2 (Sookying et al., 2011). Across these densities, no indications of poor water quality were seen; even at the higher density (45 shrimp/m^2), the maximum loading of the culture system (95 kg/ha/day) appears to be within the culture system's ability to process the nutrients. The present study was conducted at low stocking densities (10 shrimp/m^2) with maximum feeding rates at 25 kg/ha/day which based on previous studies would be well within the ponds' ability to process nutrients. However, the higher feed input applied to the culture system resulted in numerically higher TAN values (Table 2). Highest TAN was observed in treatment SFP:110, followed by SFP and SFP:90. This is logical, as it follows N loading of the culture systems. Boyd et al. (2008) calculated that increasing FCR from 1.6:1 to 2.0:1 (i.e. 25%) would lead to increasing of 27.7% and 35.8% of total phosphorus and nitrogen loading, respectively, in black tiger shrimp *Penaeus monodon* farm. Hence, 43% increase in FCR from 0.84 (SFP) to 1.2 (SFP:110) in conjunction with increased feed inputs can result in increased nitrogen and phosphorus loading of the culture system.

Shifting feed inputs by 20% (SFP:110 vs. SFP:90) resulted in limited statistical difference in production data, presumably due to the low level of replication and the high variability of pond production data. Reducing feed input of the SFP by 10% did not statistically decrease final mean yield and final mean weight. The mean yield for shrimp offered the SFP (2476 kg/ha) was significantly higher than that of SFP:110 (1707 kg/ha), but not significantly different for shrimp maintained on the SFP:90 (2040 kg/ha). Although there were no statistical differences in mean final weight, a similar pattern was repeated in the final body weight, where SFP produced the highest weight, followed by SFP:90 and SPF:110. Once the SFP was developed, an assumption was made that if feed is reduced the shrimp will be encouraged to utilize natural foods. The lack of improved performances with a 10% increase in feed input demonstrates that food was not limiting. Conversely, as feed was restricted by 10%, FCR and final mean weight were numerically lower. This indicates that food was limiting when the ration was reduced and consequently natural productivity was not capable of making up the difference. Venero (2006) evaluated the effects of variable rations with a constant protein input for *L. vannamei* in two trials. The result in pond trial after 107-121 days indicated that although differences were not statistically significant, final weights numerically reduced from 21.7 g to 19.7 g (30% CP) and 23.0 g to 22.1 g (40% CP) when feed allowance reduced from 100% to 75%. However, the result in tank trial with more controlled statistical conditions indicated that final weights of shrimp restricted feed input were significantly smaller than the shrimp fed larger rations; which were 8.1 g, 9.5 g and 10.3 g (30% CP), and 8.7 g, 10.3 g and 11.3 g (40% CP) for shrimp fed at the rations of 50%, 75% and 100%, respectively. These experiments show that although statistical research is difficult under pond conditions, the trends in ponds can be supported by more controlled conditions.

In conjunction with periodic fertilization to generate natural food, Carvajal-Valdes et al. (2012) evaluated three stocking densities and two feeding rates over an 84-day culture period in outdoor tanks. They evaluated a feed table vs. 50% reduction of feed input at three different densities (15, 25, and 35 shrimp/m^2) using outdoor cages in tanks and two replicate units. Although density resulted in a significant effect on growth, no effect of feed input on growth was found. This resulted in a decrease in FCR from 2.71 vs. 1.48 in shrimp offered a full vs. half ration, respectively, although statistical results were not reported. Based on these calculations, it is clear the reduced ration was a more appropriate level of feed input and over feeding did not improve results. Important contribution of natural food on shrimp growth in semi-intensive culture (20 shrimp/m^2 raised in cage) was also clearly stated by Anderson et al. (1987). In a pond study that 20 shrimp were stocked into bottomless cages allowing animal to access the natural food, using a $^{13}C/^{12}C$ tracer to analyze the growth carbon, the author indicated that 53-77% of the animal growth derived from pond biota, while formulated feed accounted for the remaining of 23-47% for shrimp fed with only commercial feed. This is in agreement with the results found by Gamboa-Delgado and Le Vay (2009) in which 73% of actual growth was attributed to natural food. However, Gamboa-Delgado (2013) also pointed out that the percentage of dietary feed found in shrimp stomach (2-20%) was relatively low; dietary carbon and nitrogen were comparatively larger than the proportions observed in the stomach due to high digestibility coefficients and high protein content of formulated feeds. Hence, constant availability of formulated feed is necessary due to ecological succession caused by foraging pressure and maintains abundance of natural productivity through nutrient leaching.

In the present study, shrimp growth, yield and FCR were not significantly negatively affected by reducing feed inputs by 10%. Reducing the feed ration showed significant reduction in feed cost (Table 3). While this study was conducted at a density of 10 shrimp/m^2, substantial decrease of feed cost is predicted to be more pronounced if it is applied to higher stocking density. Similar results were found in tanks; there were no significant differences in body weight among *L. vannamei* shrimp fed to satiation versus under a 25% and 50% satiation level at a 36 shrimp/m^2 density after 28 days (Nunes et al., 2006). This also points out that quite often feed tables are not specific to the conditions at a given site. Hence, it may be more appropriate to develop feed tables based on actual results at a given site. This can easily be done using on-site data for feed inputs, shrimp size and final survival. Our results were used to estimate the level of feed offered across a range of sizes using the observed data. Thus, a site specific table can be used as a feed management tool.

When managing feed inputs, it is not simply the quantity of feed that has to be considered but the quantity in relation to nutrient density or nutrient content of the diet. Reducing feed input without affecting the growth performance of cultured shrimp is possible by increasing nutrient density (Davis and Venero, 2005). Their experiment was conducted in outdoor tanks with green water from the production pond and showed that shrimp fed 40% CP at 75% ration (40CP-75%) had similar final weight to shrimp fed 30% CP at 100% ration (30CP-100%), consequently FCR was significantly smaller in shrimp under treatment 40CP-75% than those in treatment 30CP-

100%. The higher protein feed may be more expensive than lower protein feed; however, its long-term saving from reduced FCR and the benefits of reducing environmental impacts potentially produce a more cost effective system.

A primary goal of any system is to maximize marketable product, the proportion of shrimp reaching the targeted market size (e.g. $\geq$ 20 g) is a critical determinant of a farm's revenue and profit. Size distribution of head-on shrimp (Figure 2) showed that the percentage of larger shrimp produced using the SFP (98.5% of 33-55 shrimps count/kg) was higher than that for shrimp reared on either the SFP:90 and SFP:110, 93.6 and 80.3%, respectively. This might be due to adverse impacts of increasing feeding in terms of water quality or soil quality and limitations of feed in the reduced feed input. Any reduction in feed input can result in changes of economic return as feed is the major component of variable costs in intensive and semi-intensive farms (Tan and Dominy, 1997). In this study, albeit higher feed input caused higher feed cost (Table 3), the feed cost per kg shrimp produced and partial return were similar in all treatments. This confirms that the idea of increasing feed input to accelerate shrimp growth is not fully justified nor recommended in order to enhance economic performance. To obtain good economic return from commercial feeds, it is recommended that standard feeding protocols should be developed based on historical production for a given farm. By developing site specific feeding protocols, one can account for typical levels of natural foods as well as variations in growth due to site specific water quality conditions.

5. Conclusion

The growth, FCR, survival and partial return of *L.vannamei* raised in production ponds were not affected by increases or decreases in the feed ration by 10% from the standard ration. While treatment receiving 10% more feed did not indicate cost effectiveness and potentially caused environmental concerns, treatment fed 10% less feed appeared to lag behind in growth and economic performance compared to the standard feeding protocol. The standard feeding protocol is appropriate and suggested to maximizing growth performance and optimizing economic return in semi-intensive shrimp farm.

References

Achupallas, J.M., Zhou, Y., Davis, D.A., 2015. Pond production of Pacific white shrimp, *Litopenaeus vannamei* fed grain distillers dried yeast. Aquaculture Nutrition. doi: 10.1111/anu.12359

Anderson, R.K., Parker, P.L., Lawrence, A., 1987. A $^{13}C/^{12}C$ trace study of utilization of presented feed by a commercially important shrimp *Penaeus vannamei* in a pond grow-out systems. Journal of the World Aquaculture Society 18, 148-155.

Boyd, C.E., Lim, C., Queiroz, J., Salie, K., De Wet, L., McNevin, A., 2008. Best management practices for responsible aquaculture. Page 47 in USAID/Aquaculture Collaborative Research Support Program, Corvallis, Oregon State University, Oregon.

Carvajal-Valdes, R., Arjona, E., Bueno, G., 2012. Feeding rate and stocking density in semi-intensive *Litopenaeus vannamei* culture with moderate periodic fertilization. Journal of Agricultural and Biological Science 7, 899-904.

Cole, B.A., Boyd, C.E., 1986. Feeding rate, water quality, and channel catfish production in ponds. The Progressive Fish-Culturist 48, 25-29.

Davis, D.A., Arnold, C.R., 2000. Replacement of fish meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture 185, 291-298.

Davis, D.A., Samocha, T.M., Bullis, R.A., Patnaik, S., Browdy, C., Stokes, A., Atwood, H., 2004. Practical diets for *Litopenaeus vannamei* (Boone. 1931): working towards organic and/or all plant production diets. Avances en Nutricion Acuicola VII. Memorias del VII Simposium Internacional de Nutricion Acuicola. 16-19 Noviembre, 2004. Hermosillo, Sonora, Mexico.

Davis, D.A., Venero, J.A., 2005. Rethinking feeding for cultured shrimp. Global Aquaculture Advocate 8, 78-81.

Davis, D.A., Amaya, E., Venero, J., Zelaya, O., Rouse, D.B., 2006. A case study on feed management to improve production and economic returns for the semi-intensive pond production of *Litopenaeus vannamei*. Pages 282-303 in: Cruz Suarez, L.E., Maria, D.R., Salazar, M.T., Lopez, M.G.N., Cavazos, D.A.V., Cruz, A.C.P., Ortega, A.G. (Eds.), Avances en nutrición acuícola, VIII. Simposio Internacional de Nutrición Acuícola. [Advances in aquaculture nutrition, VIII. International Symposium on Aquaculture Nutrition.] Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, Mexico.

Focken, U., Groth, A., Coloso, R.M., Becker, K., 1998. Contribution of natural food and supplemental feed to the gut content of *Penaeus monodon* Fabricius in a semi-intensive pond system in the Philippines. Aquaculture 164, 105-116.

Gamboa-Delgado, J. 2013. Nutritional role of natural productivity and formulated feed in semi-intensive shrimp farming as indicated by natural stable isotopes. Aquaculture 6, 36-47.

Gamboa-Delgado, J., Le Vay, L., 2009. Natural stable isotopes as indicators of the relative contribution of soy protein and fish meal to tissue growth in Pacific white shrimp (*Litopenaeus vannamei*) fed compound diets. Aquaculture 291, 115-123.

Hopkins, J.S., Stokes, A.D., Browdy, C.L., Sandifer, P.A., 1991. The relationship between feeding rate, paddlewheel aeration rate and expected dawn dissolved oxygen in intensive shrimp ponds. Aquaculture Engineering 10, 281-290.

Martinez-Cordova, L.R., Porchas-Cornejo, M.A., Villarreal-Colemnares, H., Calderon-Perez, J.A., Naranjo-Paramo, J., 1998. Evaluation of three feeding strategies on the culture of white shrimp *Penaeus vannamei* Boone 1931 in low water exchange ponds. Aquaculture Engineering 17, 21-28.

Moriarty, D.J., 1997. The role of microorganisms in aquaculture ponds. Aquaculture 151, 333-349.

Nunes, A.J.P., Sá, M.V.C., Carvalho, E.A., Neto, H.S., 2006. Growth performance of white shrimp *Litopenaeus vannamei* reared under time and rate-restriction feeding regimes in a controlled culture system. Aquaculture 253, 646-652.

Parker, P.L., Anderson, R.K., Lawrence, A., 1989. A $\delta^{13}C$ and $\delta^{15}N$ tracer study of nutrition in Aquaculture: *Penaeus vannamei* in a pond grow-out system. In: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), Stable Isotopes in Ecological Research. Springer-Verlag, New York, pp. 288-303.

Piadad-Pascual, F., 1993. Aquafeeds and feeding strategies in the Philippines. Pages 317-343 in: New, M.B., Tacon, A.G.J., Csavas, I. (Eds.), Farm-made aquafeeds. Proceeding of the FAO/AADCP, Bangkok, Thailand.

Piedad-Pascual, F., Cruz, E.M., Sumalangcay, A., 1990. Supplemental feeding of *Penaeus monodon* juveniles with diets containing various levels of defatted soybean meal. Aquaculture 89, 183-191.

Reymond, H., Lagardtre, J.P., 1990. Feeding rhythms and food of *Penaeus japonicus* Bate (Crustacea, Penaeidae) in salt water ponds: role of halophilic entomofauna. Aquaculture, 81, 125-143.

Roqued'Orbcastel, E., Blancheton, J.B., Aubin, J., 2009. Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. Aquaculture Engineering 40, 113-119.

Roy, A.L., Bordinhon, A., Sookying, D., Davis, D.A., Brown, T.W., Whitis, G.N., 2009. Demonstration of alternative feeds for the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters of west Alabama. Aquaculture Research 40, 490-503.

Sookying, D., de Silva, S.F.D., Davis, D.A., Hanson, T.R., 2011. Effects of stocking density on the performance of Pacific white shrimp *Litopenaeus vannamei* cultured under pond and outdoor tank conditions using a high soybean meal diet. Aquaculture 319, 232-239.

Talbot, C., Corneillie, S., Korsøen, O., 1999. Pattern of feed intake in four species of fish under commercial farming conditions: implications for feeding management. Aquaculture Research 30, 509-518.

Tan, R.K.H., Dominy, W.G., 1997. Commercial pelleting of crustacean feeds. Pages 520-549 in: D'Abramo, L.R., Conklin, D.E., Akiyama, D.M. (Eds). Crustacean Nutrition. World Aquaculture Society, Advances in World Aquaculture 6, Baton Rouge, Louisiana.

Thakur, D.P., Lin, C.K., 2003. Water quality and nutrient budget in closed shrimp (*Penaeus monodon*) culture systems. Aquaculture Engineering 27, 159-176.

Tidwell, J.H., Webster, C.D., Yancey, D.H., D'Abramo, L.R., 1993. Partial and total replacement of fish meal with soybean meal and distillers' by-products in diets for pond culture of the freshwater prawn (*Macrobrachium rosenbergii*). Aquaculture 118, 119-130.

Trino, A.T., Pen, V.D., Bolivar, E.C., 1992. Growth and survival of *Penaeus monodon* juveniles fed a diet lacking vitamin supplements in a modified extensive culture system. Aquaculture 101, 25-32.

Venero, J.A., 2006. Optimization of dietary nutrient inputs for Pacific White shrimp *Litopenaeus vannamei*. Doctoral dissertation. Auburn University, Auburn, Alabama, USA.

Venero, J.A., Davis, D.A., Rouse, D.B., 2007. Variable feed allowance with constant protein input for the Pacific white shrimp *Litopenaeus vannamei* reared under semi-intensive conditions in tanks and ponds. Aquaculture 269, 490-503.

White, P., 2013. Environmental consequences of poor feed quality and feed management. In: Hasan M.R, New M.B. (Eds.), On-farm feeding and feed management in aquaculture, FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Zelaya, O., 2005. An evaluation of nursery techniques and feed management during culture of marine shrimp *Litopenaeus vannamei*. Doctoral Dissertation. Auburn University. Auburn, Alabama, USA.

Table 1 The price of shrimp for different size groups. The price is used based on the publication of Sookying (2011).

Count (shrimp/lb)	Count (shrimp/kg)	Price ($/lb)	Price ($/kg)
≤ 15	≤ 33	2.00	4.4
16-20	34-43	1.80	4.0
21-25	44-55	1.65	3.6
26-30	56-66	1.60	3.5
31-35	67-77	1.55	3.4
36-40	78-88	1.50	3.3
41-50	89-110	1.40	3.1
51-60	111-133	1.20	2.6
61-70	134-155	1.10	2.4

Table 2 Summary of water quality fluctuations observed over the 17-week culture period of *L.vannamei*, fed commercial diets at three level of feeding rations in 0.1-ha ponds. The values are shown in mean ± standard deviation and minimum to maximum values in parenthesis.

Parameter	SFP:90	SFP	SFP:110
Temperature (°C)			
am	29.71 ± 1.67 (22.6, 32.5)	29.25 ± 1.65 (23.10, 31.90)	29.32 ± 1.70 (22.20, 32.30)
noon	32.25 ± 1.98 (25.80, 35.90)	31.43 ± 0.52 (25.80, 34.30)	31.53 ± 1.89 (25.50, 35.20)
pm	32.00 ± 1.94 (26.1, 35.90)	31.24 ± 1.71 (26.10, 34.10)	31.48 ± 1.84 (25.90, 34.60)
DO[a] (mg L^{-1})			
am	4.68 ± 1.36 (1.56, 10.17)	4.56 ± 1.29 (2.35, 8.20)	5.13 ± 1.40 (1.51, 10.08)
noon	13.43 ± 3.65 (5.11, 22.68)	12.45 ± 3.29 (3.92, 19.92)	11.51 ± 3.05 (2.49, 22.00)
pm	12.57 ± 3.79 (3.96, 27.49)	11.33 ± 3.31 (2.84, 23.91)	11.13 ± 3.68 (3.01, 26.12)
pH			
am	8.13 ± 0.77 (6.59, 9.91)	8.18 ± 0.71 (6.94, 9.78)	7.91 ± 0.81 (6.21, 9.71)
noon	9.34 ± 0.59 (6.96, 10.28)	9.41 ± 0.52 (7.67, 10.48)	9.29 ± 0.52 (7.45, 10.95)
pm	9.26 ± 0.63 (6.59, 10.51)	9.39 ± 0.48 (7.73, 10.80)	9.23 ± 0.62 (6.33, 11.10)
Salinity (ppt)			
am	5.39 ± 4.11 (1.59, 16.7)	2.94 ± 1.61 (1.19, 8.48)	3.01 ± 2.74 (1.02, 10.79)
noon	5.42 ± 4.13 (1.58, 16.49)	2.97 ± 1.65 (1.19, 8.64)	3.08 ± 2.30 (1.01, 10.88)
pm	5.50 ± 4.13 (1.58, 16.54)	2.98 ± 1.66 (1.19, 860)	3.07 ± 2.31 (1.01, 10.89)
Sechi (cm)	43.47 ± 34.53 (5,150)	35.97 ± 27.80 (10, 140)	46.57 ± 34.35 (10,150)
TAN[b] (mg L^{-1})	0.04 ± 0.18 (0.00, 1.00)	0.07 ± 0.20 (0.00, 1.00)	0.14 ± 0.47 (0.00, 3.00)

[a] Dissolved oxygen

[b] Total ammonia-nitrogen

Table 3 Mean production parameters of juvenile Pacific white shrimp, *L. vannamei* (119 mg mean initial weight), fed three feeding rations after a 17-week growth trial in 0.1-ha ponds. Values within columns with the different letters are significant difference ($P < 0.1$) based on analysis followed by Student Newman-Keuls multiple range test.

Parameter	Yield (kg/ha)	Final mean weight (g)	FCR[a]	Survival (%)	Production value ($/ha)	Feed cost ($/ha)	Feed cost ($/kg shrimp produced)	Partial return[c] ($/ha)
SFP:90	2040[xy]	30.7	0.92	63.9	8459	2001	0.99	6459
SFP	2476[x]	35.3	0.84	67.1	10703	2224	0.90	8479
SFP:110	1707[y]	27.2	1.20	65.7	8095	2425	1.29	5671
P value	0.0506	0.2895	0.3152	0.9594	0.4552		0.3128	0.4263
PSE[b]	160.5	3.4	0.17	7.9	151.2		0.18	150.5

[a]FCR: Feed conversion ratio

[b]PSE: pool standard error.

[c]Partial return=production value-feed cost

SFP:110 (n=3); One pond was excluded from treatment SFP (n=2) and treatment SFP:90 (n=2) due to initial mortality resulting low survival.

Figure 1 Feed input of three treatments over 17-week culture

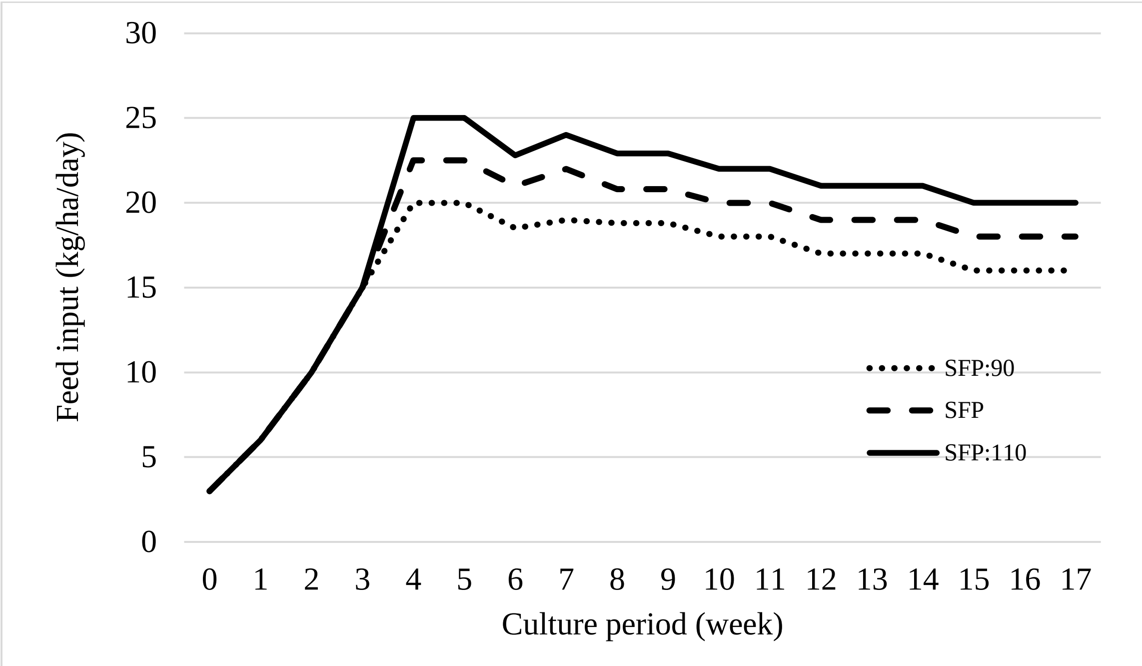
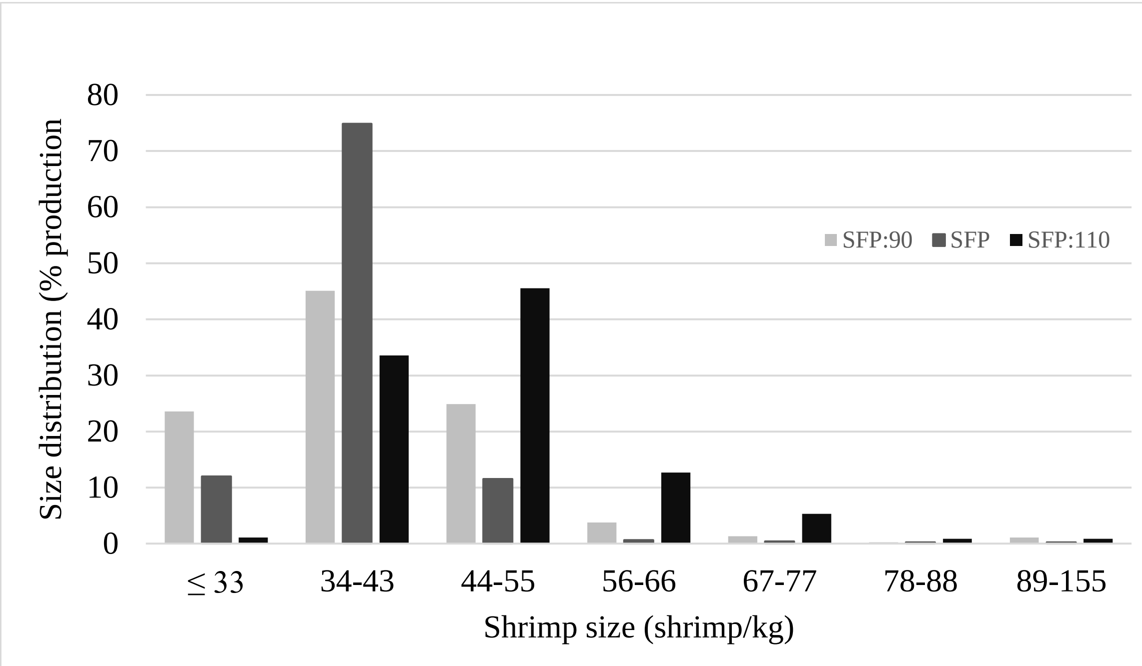


Figure 2 Shrimp size distribution in count/kg with head on after 17-week pond production trial of *L.vannamei*, fed different feeding rations.



CHAPTER III

EVALUATION OF FEEDING RATES FOR PACIFIC WHITE SHRIMP *Litopenaeus vannamei* REARED IN GREEN WATER TANKS AND PRODUCTION PONDS

Abstract

The aim of this study was to refine the current feed management strategies and evaluate the effects of feeding rates on the growth performance, production and economic returns of semi-intensive pond production of *Litopenaeus vannamei*. Two growth trials, including an outdoor tank trial and pond trial, were carried out. In the tank trial, shrimp with an average weight of 0.76 g were stocked at a density of 30 shrimp/tank (35 shrimp/m^2). The commercial diet (35% Protein & 8% Lipid) was offered at various feeding rations to shrimp in four replicate tanks per treatment over a 6-week period. Shrimp were offered feed based on a standard feeding protocol (T100) with five variations of this protocol produced by varying the feed inputs and expressing the treatments as a percentage (e.g. T90 is 90% of the standard protocol). The results for the tank trial showed no significant differences in mean survival rate and FCR among treatments, which ranged from 95.8 to 99.2% and 0.76 to 0.87, respectively. The mean final weight (11.5 g) and weekly weight gain (1.86 g) of shrimp maintained on the T110 feed protocol were higher than final weight (10.2 g) and weekly weight gain (1.58 g) of shrimp maintained on the T90 protocol, but not significantly different from the remaining treatments. Feed cost to produce each kg of shrimp for the phased feeding treatment T80:90:100 ($1.14/kg) was similar to all other tested groups, exception for T110 ($1.32/kg). In the pond trial, juvenile shrimp (28.8 ± 2.74 mg) were pooled across nursery tanks and stocked into twelve 0.1-ha ponds at a density of 28 shrimp/m^2 with four replicates per treatment. Shrimp were fed with a sinking commercial feed (35% CP and 7% Lipid) twice per day. Three feeding protocols were evaluated including a standard feeding protocol (SFP), a 10% reduction in the SFP (SFP:90), and a variable feed input (SFP:80:90:100),

which included 80% SFP at wk 4^{th} - 8^{th}, 90% SFP from wk 9^{th} - 12^{th} and 100% SFP for wk 13^{th} - 16^{th}. The results for ponds showed no significant differences in mean growth performance and economic return among tested feeding protocols. Survival ranged from 63.4 to 65.8%. Mean final weight was not significant different in treatments having less feed input (SFP:90 and SFP:80:90:100) from those in treatment fed with SFP. Mean FCR was between 0.99 and 1.03. Reducing feed input resulted in significant reduction in feed costs, indicating the feasibility in reducing variable costs for farm operation. However, feed cost per production unit was similar in all treatments varying from 0.97 to 1.02. The greatest percentage of large shrimp in SFP resulted from receiving full feed ration indicated improved economic return for SFP. These studies demonstrated that feed input can be either applied at a standard ration to optimize growth and increase economic return, or at restricted rations to reduce FCR (feed cost) albeit at the expense of some growth. Increasing the ration did not result in improved growth performance or cost efficiencies. Overall, the results of this study and previous studies indicate that it is not economically beneficial to use high feed inputs. A cost effective ration should be based on the knowledge of site specific conditions the influence shrimp growth and required nutrient inputs.

1. Introduction

Crustaceans are an important component of global aquaculture in terms of quantity and value. Farmed crustaceans accounted for 6.4 million tonnes with a value of US $30.9 billion in 2012 (FAO 2014). Among farmed crustacean species, shrimp is the most important. Shrimp aquaculture represents one of the fastest growing sections of the global seafood industry increasing from 1.1 million tonnes in 2000 to nearly 3.78 million tonnes in 2010 (FAO, 2012). Fast growth of shrimp production is primarily attributed to intensification of pond aquaculture that requires increasing additional input resources per unit of culture area including stocking density, feed, energy and management. Tacon et al. (2015) estimated that in 2012 shrimp feed ranked third (6.18 million tons or 16 %) after tilapia feed (6.67 million tons or 17 %) and carp feed (11.03 million tons or 28 %) in global production of commercial feed. It is well documented that feed cost makes up more than 50 percentage of operating cost and that feed costs are reflections of ingredient and manufacturing costs. Therefore, any increase in ingredient cost will potentially raise the feed cost, eventually affecting the farm revenue and profit. In addition to concern in economic efficiency, inappropriate use of feed potentially causes negative impacts on the culture system. Boyd et al. (2007) estimated that about 10 to 30% nutrients absorbed across the gut became gained biomass whereas the remainder (food-derived wastes) entered water with three main forms including uneaten feed, feces and excreta.

Using nutritionally complete feeds and adopting good feed management can improve production efficiency and reduce the environmental impacts of the feed (De Silva, 1989; Mohanty, 2001; Davis et al., 2008). It is generally recommended that using high quality feed will result in better cost effectiveness due to increasing digestibility and reduced nutrient loading on the culture system. Shipton and Hasan (2013) noted that the use of poor formulated feeds that fails to meet the nutritional requirements of culture species unavoidably caused inefficiencies and increased production costs. Nutritionally-balanced feed is a prerequisite to lucrative production; nevertheless, the final success will largely depend upon whether appropriate application technologies are implemented (Tacon, 2002; Davis et al., 2006). Good management practices promote appropriate feed intake and minimize nutrient losses. Ensuring adequate feed inputs and feed consumption for shrimp is not an easy task and varies under biological, environmental and human factors. Therefore, it is appropriate to develop a comprehensive feeding program based on observation and knowledge accumulating over time at each farm for each culture species and each type of feed (Mohanty, 2001; Zelaya, 2004). Although adoption of good feeding practice is complicated, primary considerations in pond management are well known and discussed below.

Feed ration estimation

Feed allowance can be determined using a number of techniques and each technique has its own advantages and disadvantages. Traditionally, feed inputs are calculated based on standard feed tables and estimates of biomass in the pond derived from an average shrimp weight and estimated survival. This method is suitable for pond management to some extent but is influenced by the population estimation and design of the feed table. Sampling shrimp to estimate populations is labor intensive and it is often misleading. Moreover, feed tables tend to underfeed at the beginning and overfeed towards the end of a crop resulting in high FCR. A variant on feed tables is to forecast feed inputs based on historical and observed performance. In this case, feed inputs are based on back calculations to predict survival, growth rate and a desired FCR. The advantage of this is that one can target the best observed FCR that is specific to the site as opposed to using a feeding table that is not specific to the feed or the site conditions. Davis et al. (2008) pointed out that biggest weakness of most feeding protocols is that they require and accurate prediction of survival. Naturally, higher survival than predicted ones lead to underfeeding, while lower survival than predicted causes overfeeding, potentially degrading the pond bottom. Hence, each farm should keep the record of the shrimp survival and production which can be helpful in determining accurately the feed input ration.

Feed frequency and feed distribution

The labor cost for feeding shrimp ponds can account for a significant percentage of variable costs (Lawrence and Lee, 1997). It is generally believed that the more frequently feed is applied, the better growth rate and feed efficiency are likely to be (Sedgwick, 1979; Nunes and Parson, 2000). However, economic efficiency to a great extent depends on other factors such as cost of labor to apply the feed and the feed conversion efficiency. Hence, the number of daily feedings should be decided based on the farm size, availability of labor and total daily feed ration. For large grow-out ponds, it is typically not practical to feed more than two times per day as a more intensive labor method is not desirable. In addition, the aim of feeding frequency is to deliver feed at the rate in which nutritional needs are met at the least labor cost possible. It has been reported that digestive processes in shrimp complete within 4-6 hours at 20^0C (Goddard, 1996) and moderate feed input between 2-4 times/day are recommended (Wyban and Sweeney, 1991; Carvalho and Nunes, 2006). Unlike fish, shrimp do not travel long distances to get feed. Quite often feed is evenly distributed over a large portion of the pond ensuring shrimp have equal change to obtain the feed. Concentrating feed in a small area is typically avoided because uneaten feed and waste can build up reducing the bottom soil quality and it can cause competition and eventually size variations are inevitable (Fox et al., 2001). Therefore, distribution methods need to ensure that majority of shrimp in the pond can obtain the feed at the lowest cost spent on foraging.

Nutrient density and availability of natural food

It is important to understand that animal feed up to a certain level to satisfy their requirement of nutrient rather to consume a quantity of feed (Hepher, 1998). Hence, feed input should not simply be adjusted by quantity but by nutrient density of feed. Kureshy and Davis (2002) and more recently Davis et al. (2008) demonstrate this concept in shrimp. They concluded that feed containing high concentrations of nutrients should be fed at lower levels than those with lower level of nutrients. Bombeo-Tuburan et al. (1993) analyzed the gut content of *P. monodon* reared in extensive ponds without supplementary feed showed that the most common food taken was detritus, diatoms, cyanobacteria and green algae. In semi-intensive systems, the contribution of natural food and bacterial flock are still considered to be important, attributing 53-77% growth (Anderson et al., 1987) and 70-80% of the weight gain of *L. vannamei* (Bianchi et al., 1990). In ponds, besides directly supplying food for cultured animal, micro-organisms play an essential role in maintaining the health and stability of aquatic ecosystems by processing uneaten feed and waste products (Moss and Pruder, 1995; Bratvold et al., 1999; Tacon et al., 2000). However, the abundance of natural productivity largely depends on fertility, stocking density and season. Hence, proper feed management requires understanding the interaction of external and internal factors influencing availability of natural productivity.

Environmental conditions

Water temperature and dissolved oxygen (DO) are two main factors affecting feeding consumption and animal metabolism (Allan and Maguire, 1991; Wyban et al., 1995; Fox et al., 2001). For example, shrimp are poikilothermic; so metabolism, growth and feed intake are tied to temperature. Ponce-Palafox and Martinez-Palcacios (1997) found that at a salinity of 30 ppt, the specific growth rates of *L. vannmei* after 40-day culture numerically increased with increasing temperature, which were 3.37, 6.85 and 7.37 g/d at temperatures of 20, 25 and 30^{o}C, respectively. When DO concentrations are lower than 3 mg/L, it can cause severe stress for shrimp and is often associated with increasing ammonia, so feeding should be avoided (Andrews et al., 1973; Diaz and Rosenberg, 1995). In practice, when environmental stress occurs or is anticipated, feed inputs should be reduced to minimize the stress. For instance, days with heavy cloud cover or occurrence of algae die-off often results in low DO; decision to reduce or stop feeding should be considered.

Although advanced genetics and nutritional knowledge have improved significantly allowing farmer to access high quality feed, potential of significant improvement in performance can only be fully expressed if appropriate feeding strategies are practiced (Davis and Venero, 2005; Zeigler, 2014). If feeding is poorly managed, the performance of high quality feed is nothing better than expensive fertilizer. Conversely, well-managed feeding programs will deliver proper feed rations to meet nutritional demands and suit feeding behaviors of culture animals at different development stages, ensuring nutrients from artificial feed and natural food being utilized efficiently. Despite its importance, published information of feeding strategies for shrimp in pond-based farming systems is not well investigated. Therefore, the objectives of this study were to systematically evaluate the effects of different feeding rates on growth performance and economic returns for Pacific white shrimp *L. vannamei* reared in ponds and green water tanks.

2. Materials and Methods

Research was conducted at the Alabama Department of Conservation and Natural Resources, Marine Resources Division, Claude Peteet Mariculture Center in Gulf Shores, Alabama. Pacific white shrimp *L. vannamei* post-larva were obtained from Shrimp Improvement Systems, Islamorada, Florida, and nursed for 17 days. Two growth trials including an outdoor tank trial and pond trial were carried out.

Outdoor tank trial

A 6-week tank trial was conducted in an outdoor green water semi-recirculating system designed to mimic pond conditions. Shrimp was pooled from the nursery system and chosen by hand-sorting to uniform size (around 0.76 g/shrimp). Each tank was stocked with 30 shrimp (or 35 shrimp/m^2). The culture system consists of twenty-four circular polyethylene tanks designed to hold 800 L of water, as well as 800-L reservoir tank, circulation pump, and supplemental aeration. Culture water was pumped 3 hours daily from a production pond to reservoir tank at a rate of 30 L/min in order to allow a 100% water exchange every 3.5 days. A 1-hp regenerative blower provided air to each tank and reservoir through air stones.

The test diet (35% CP and 8% Lipid) manufactured by Rangen, Inc., Angleton, Texas was offered at various feeding rates to shrimp in four replicate tanks per treatment throughout the 6-week period. Similar to the pond trial, the SFP for tanks (T) was calculated using an expected growth of 1.3 g/wk, an FCR of 1.2 with 100% survival. The SFP feed input was manipulated to allow systematic manipulations. Six treatments or feeding protocols (Table 1) are described as follows:

- T80:90:100: The feed ration was changed over 2 wk-culture period starting from 80% SFP for the first 2 weeks, increasing to 90% SFP for the next 2 weeks and using 100% SFP for the last 2 weeks.
- T90: 90% SFP was used over 6 wk-trial (equivalent to reducing 10% SFP).
- T90:100: Percentages of feed input began with 90% SFP for the first 3 weeks, then increased to 100% SFP for the last 3 weeks.
- T100 (SFP): Standard feeding protocol (or reference treatment).
- T100:110: 100% SFP was used for 3 weeks then increasing to 110% SFP for next 3 weeks.
- T110: shrimp was fed at the rate of 110% SFP (or 10% increase of SFP).

Pond trial

Ponds utilized in this research were approximately 0.1 ha in water surface area (46 x 20 x 1.0 m). The pond bottom was covered with 1.52-mm thick high polyethylene liner and coated with 25 cm of sandy-loam soil; the bottom of each pond was tilled prior to filling with brackish water. Water inputs were screened by 10-cm encasement sleeve 100% nylon with the mesh size of 250 µm to eliminate predatory organisms and limit unwanted larvae. A rectangular catch basin (183 x 209 cm) and the standpipe (20 cm in diameter) were present in each pond. Supplemental aeration was provided by using a 1 or 2-hp aerator depending on available equipment (1 hp Model F1000DP, The Power House Inc., Owings Mills, MD, USA or 1-hp or 2-hp Aire-O2, Aeration Industries International Inc., Minneapolis, MN, USA) to try to keep dissolved oxygen (DO) above 3 mg/L for all ponds. This trial was conducted with minimal water additions primarily done to make up for water losses caused by evaporation. In order to promote natural productivity, two weeks prior to stocking, all ponds were fertilized with a mixture of inorganic liquid fertilizers (32-0-0 and 10-34-0) at the application rate of 1,697 ml and 303 ml, respectively, providing 5.73 kg N and 1.03 kg P_2O_5 per ha. With the target of maintaining Secchi disk readings between 25 and 40 cm, a second fertilization was applied for ponds having transparency above 60 cm.

At the termination of nursery phase, shrimp (28.8 ± 2.74 mg) pooled from nursery tanks were stocked into twelve 0.1-ha ponds at a density of 28 shrimp/m^2 with four replicates per treatment. Over the first two weeks, the shrimp were fed 1.5 mm pellet then during the next two weeks a 2.0 mm short cut feed containing 40% crude protein (CP) and 9% lipid produced by Zeigler, Inc. (Gardners, PA, USA). After four weeks of culture, mean shrimp size was 6.55 ± 2.36 g. Shrimp were then fed with the sinking commercial feed (35% CP and 7% Lipid) manufactured by Zeigler, Inc. based on the assigned feed treatments. Three feeding protocols were evaluated. The standard feeding protocol (SFP or reference treatment) was calculated based on an assumption of 1.3 g growth rate per wk, estimated feed conversion ratio (FCR) of 1.2, and predicted survival rate of 75% over 16-wk culture period. The tested treatments included a 10% reduction in feed from the SFP (SFP:90) and a phased feeding (SFP:80:90:100) for which feed input were changed every 4-wks, starting from 80% SFP at wk 4^{th} - 8^{th}, increasing to 90% SFP for wk 9^{th} - 12^{th} and 100% SFP for wk 13^{th} - 16^{th}. The actual feeding input throughout the production cycle is presented in Figure 2.

Water quality parameters, including temperature, dissolved oxygen, salinity and pH, were measured in the morning (0500 h-0530 h), afternoon (1400 h-1430 h) and evening (2000-2200 h) by YSI (Yellow Spring Instrument Co., Yellow Spring, OH, USA). Water samples were taken in all ponds to measure total ammonia-nitrogen (TAN) using an Orion ammonia electrode probe (Thermo Fisher Scientific Inc., Waltham, Massachusetts) on a weekly basis. Secchi disk readings for each pond were monitored once per week. To track growth and the health of the shrimp, they were sampled once a week using a cast nest (1.22 m radius and 0.95 cm mesh size). Approximately, 60 shrimp per pond were group weighed and visually inspected for general health.

After a 16-week culture period, shrimp were harvested. A day prior to harvest, feed input was ceased; about two thirds of the water was withdrawn from the pond and an aerator placed above the catch basin to ensure adequate DO levels. On the following day, the aerator was removed, the remaining water was drained and the shrimp were pumped from the catch basin with a fish pump (Aqualife- Life pump, Magic Valley Heli-arc and Mfg, Twin falls, Idaho) equipped with a 25-cm diameter suction pipe, dewatered, collected and transferred to a truck. Collected shrimp were rinsed and weighed. Approximately 150 shrimp from each pond were randomly sampled to measure individual weight. Mean final weight, final yield, FCR, survival and size distribution were determined.

Biochemical analysis

On the day of termination, 10 shrimp for each pond and 5 shrimp for each tank were randomly selected and frozen at -20°C for subsequent determination of whole body composition. Moisture content was determined by drying to constant weight at 105°C. The determination of crude protein was done by the Kjeldahl method (Williams, 1984). A semi-micro abiotic bomb calorimeter (Model 1425, Parr Instrument Co. Moline, IL, USA.) was used to determine energy.

Economic analysis

Production value was calculated by multiplying the production and farm gate prices. The detail of selling prices for each size classes were presented in Table 9. Partial return was determined by subtracting feed cost from production value. During the first four week of the pond trial, shrimp were offered feed containing 40% CP and 9% Lipid (US $1.9//kg feed); afterwards, shrimp were fed with less expensive feed (US $0.95/kg) containing 35% CP and 8% Lipid produced by Zeigler, Inc. Meanwhile for the tank trial, the feed containing 35% CP and 8% lipid produced by Rangen, Inc. costing US $1.08/kg was utilized. To determine feed cost of production unit, feed cost was divided by the number of kg shrimp produced.

Statistical analysis

Statistical analyses were conducted using SAS 9.4 (SAS Institute, Cary, NC, USA). Data were analyzed using one-way analysis of variance to determine if significant differences existed among treatments, followed by the Student-Neuman-Keuls multiple range test to determine the differences among treatment means. Significant differences among treatments were determined at a probability level of $P < 0.05$ for both outdoor tank and pond data.

3. Results

Outdoor tank trial

The water quality parameters over the 6-wk tank trial were adequately maintained for growth and survival of shrimp. The mean morning and afternoon water quality variables are presented in Table 2. The growth performance and feed cost per production unit were evaluated at the end of 42 days. No significant differences in mean survival among tested feeding protocols existed; all treatments showed survival rates greater than 95% (Table 3). No significant differences in mean FCR (0.76 to 0.87) were observed among groups. The mean final weight in treatment T110 (11.2 g) was higher than that in treatment T90 (10.2 g) but not statistically different from the remaining treatments. Mean percent weight gain was between 1306 and 1459% after 6 weeks of culture. T90 had the lowest mean weekly weight gain (1.58 g/wk) and final biomass (298 g); and these were lower than those of T110, which were 1.86 g/wk and 354 g biomass, respectively.

Table 4 summarized the biochemical composition of whole body shrimp samples after 6-week culture experiment. Mean percentages of dry matter were insignificantly different across the tested feeding protocols, varying from 23.3 to 24.5%. Similarly, no significant differences were found in either mean protein (66.7 to 68.5%) or energy content (4643 to 4757 Kcal/g) of whole body. Feed cost per production unit was significantly lower in T80:90:100 ($1.14/kg) than in T110 ($1.32/kg), but there were insignificant differences from the other groups.

Pond trial

Over the 16-week culture period, water conditions were monitored and maintained in the typical ranges for pond production of *L. vannamei*. The water quality variables averaged (±SD) for three treatments were as follows: salinity, 11.06 ± 1.23 g/L; dissolved oxygen, 8.38 ± 2.14 mg/L; temperature, 31.16 ± 1.54^{o}C; pH, 8.5 ± 0.44. These presented parameters were suitable for shrimp growth and health. The detailed water quality for treatments classified by morning, afternoon and night were summarized in Table 5. The Secchi disk readings fluctuated during the culture season depending upon algae bloom and die-off. Pond water was relatively clear initially (Secchi disk 90-130 cm) and became progressively more turbid as the algae developed. Sporadic algae crashes caused high TAN-N in various ponds (2, 3 and 6 mg/L for SFP:80:90:100, SFP:90 and SFP, respectively). However, over the culture period, the overall mean of Secchi disk readings and TAN-N were typical for pond production conditions for this species (Table 5).

One pond (SPF:80:90:100 treatment) was excluded due to an electric failure around midnight that led to low DO levels and subsequently poor survival. Shrimp were harvested after 16 weeks of culture and the mean weights were 27.2, 26.1 and 25.8 g for SFP, SFP:90 and SFP:80:90:100, respectively. Mean survival ranged from 63.4 to 65.2% and mean FCR varied from 0.99 to 1.02 (Table 6). Greatest weekly weight gain was observed in SFP, with 1.70 g/wk followed by SFP:90 and SFP:80:90:100 with 1.63 and 1.61 g/wk, respectively. No significant differences were found in biomass across the treatments, which ranged from 4625 to 4863 kg/ha.

Dry matter, energy and protein contents of shrimp are presented in Table 12. Mean percentages of dry matter were similar in all treatments, varying between 24.8 and 25.3%. Mean protein content (63.5 to 64.7%) and energy (4585 to 4687 kcal/g) were not affected by different feed input rations.

The mean production value was numerically smaller for treatments receiving restricted feed input rations ($18444 for SFP:90 and $18606/ha for SFP:80:90:100) compared to treatment receiving full ration ($19581/ha for SFP) but they were not statistically significant different. There was a general trend towards declined feed cost as feed input was reduced; being lower in SFP:90 and SFP:80:90:100 than in SFP (Table 11). However, economic analysis demonstrated that feed cost per unit of shrimp produced were uniformly low among treatments, varying from $0.97 to $1.02/kg. Likewise, insignificant differences in partial return was observed, being estimated at $13889, $14645 and $14070/ha for SFP, SFP:90 and SFP80:90:100, respectively.

4. Discussion

Feed cost normally accounts for 40-60% of total production cost in shrimp culture (Chanratchakool et al., 1994; Lovell, 1998; Hertrampf and Piedal-Pascual, 2000, De Silva and Hasan, 2007). This large component of variable costs substantially influences profitability of farm operations. Developing and applying appropriate feeding strategies are essential to ensure the optimization of feed use, which governs the farm production, FCR, water pollution, nutrient loading and economic returns. There is no fixed formula for successful feed management. Optimizing feeding practices is site specific and greatly depends on continuous review of historical records of stocking density, production, growth and feeding methods. Quantifying feed inputs in a shrimp farm is more difficult than that in a fish farm where floating feeds can be used to observe feeding. Shrimp forage on the bottom and eat slowly; so water stable sinking feeds are utilized. Unlike for fish, shrimp feed consumption cannot be easily made right after feeding and the true population is seldom known.

In order to more precisely evaluate the response to feed inputs, a portion of this research was conducted in outdoor tanks for which populations are known and water quality is equalized. The 6-week culture period was broken down into intervals and feed inputs adjusted to see the response of the shrimp. This allowed for different feed inputs across the culture period or in selected periods to possibly allow for the consumption of natural foods. A simple way to envision the response is to regress feed input against shrimp final weight (Figure 1a). In this case, the slope is significant (P=0.0067), the adjusted R square is very poor (0.2571). It appears that as timing of feed inputs was also changed this model, but does not take this into account and results in increased variation. Simplifying the data set to the 90, 100 and 110 treatments also produces a significant model but a stronger Adjusted R square of 0.5827 (Figure 1b). The most restrictive feed input (T90) resulted in significant reductions in weight gain and biomass demonstrating that feed could be limiting and natural foods were not capable of meeting the needs of the shrimp. Interestingly, the shrimp weight in T80:90:100 was not negatively affected although the amount of feed restricted in T80:90:100 and T90 was equal (10% reduction). This demonstrates that feed can be restricted without compromising shrimp growth but it must be appropriately timed. The T80:90:100 protocol was designed to increase the intensity of feed restriction towards the beginning of culture period. Studies by Nunes and Parsons (2000) as well as Morthy and Altaff, (2002) have indicated that smaller shrimp have a higher intake of natural foods than older shrimp. Hence, it is more likely the feed inputs can be restricted early in the production cycle as compared to later in the cycle. The remaining treatments (T90:100, T100, T100:100 and T110) showed similar growth performance demonstrating additional amount of feed did not result in significant growth and FCR improvement. Similar results were found in the study of Roy et al. (2012) in which an increase of 10% feed input from SFP did not result in better growth rate, survival and FCR. In addition to restricting feed to account for natural productivity, feed inputs must be adjusted for nutrient density of the diet. Patanaik and Samocha (2009) demonstrated that *L. vannamei* raised in outdoor tanks for 118 days and fed 36% CP at 84.2% ration had similar growth and survival to shrimp fed 30% CP at 100% ration, but the FCR of the former (1.38) was significant smaller than that of the latter (1.82).

From the biological point of view, it is reasonable to maximize ration for maximum growth. However, it may not be economically worthwhile if economic gains of increased biomass are smaller than the increased costs associated with increasing the ration. In this study, it was likely that the feed cost per unit of production increased as feed input increased ($1.28, $1.30 and $1.32 for T100, T100:110 and T110, respectively). This could be attributed to the fact that shrimp did not eat the excessive amount of feed provided in T100:110 and T110 once nutritional needs were already satisfied at a standard ration and uneaten feed became wastes leading the economic inefficiency. In contrast, there was a trend towards improving FCRs (0.76, 0.85 and 0.84) and reducing feed cost per kg of shrimp produced ($1.14, $1.29 and $1.28 for T80:90:100, T90 and T90:100, respectively) when the feed input was restricted. That was probably due to the restricted feed rations being efficiently utilized by shrimp and converted to growth or biomass and/ or animals responded to restricted feed rations by consuming natural food to compensate for the nutrient limitations from the feed. Venero et al. (2008) concluded that the nutrient requirements of *L. vannamei* can be met with a variety of protein and feed input levels as long as the level of nutrients is adequate. In his study, at a constant DE:CP ratio, survival and growth of shrimp fed 30% CP at 100% ration were similar to that of shrimp fed 40% at 75% ration, but the FCR was significantly smaller in treatment 40CP-75% (1.62) than in treatment 30CP-100% (2.09). This demonstrates that as nutrient density of the diet is increased, FCR is improved. Albeit high density diet may be more expensive than low density diet, the benefits of using the former may outweigh the costs due to improving FCR and potentially reducing water quality problems.

Results of the tank trial as well as those presented in a study of feed management by Davis et.al (2006) indicated that pond-based research should concentrate on reducing feed inputs as there has been no evidence that increasing feed inputs above SFP has resulted in improved performance. In contrast, the reduction of feed input appears to improve the FCR while only having minor impacts on the growth performance. Hence, the pond trial with more practical implication was conducted to evaluate the concept of reducing feed input based on the standard feeding ration. The SFP using targeted FCR has been used in this site for several years with good results. Davis et al. (2006) compared the growth performance of *L. vannamei* fed based on a feed table (FT) vs. targeting FCR of 1.6, survival of 85% and average growth of previous week (fixed FCR). At stocking density of 35 shrimp/m^2, after 14-week-culture, the authors found no significant differences in final weight (13.6 g and 13.9 g for FT and fixed FCR) between two feeding methods; however, the FCR (2.03 for both treatments) was very high. In their study, feed input in fixed FCR stayed consistent between 80-100 kg/ha/day since the third week of culture, whereas it was 80 kg/ha/day by the fifth week and continued to increase to 150 kg/ha/day for the last week in FT. This clearly demonstrates the increase of feed input towards the end of production cycle resulted in no improvement in growth performance and FCR. Historical records for pond production in this research site showed that the FCR tended to improve with decreasing feed input: FCR of 2.5-2.7 with the feed input of 9000 -9600 kg/ha (Zelaya, 2005), FCR of 1.5-1.8 with the feed input of 6500-7960 kg/ha (Zalaya, 2005), and FCR of 1.37-1.45 with the feed input about 5862 kg/ha (da Silva, 2013). This suggests that excessive feed input resulted in poor FCR. These results indicate there needs to be restriction in feed supply to encourage shrimp to consume natural food available in ponds.

It is important to note that the amount of feed intake is to a great extent regulated by nutritional demand. For example, if the amount of feed input fails to satisfy the energy need, by natural instinct animals will actively search and consume edible food sources to make up the difference ensuring the normal metabolic functions. Roy et al. (2012) studied the effects of feeding rates and pond primary productivity on growth performances of *L. vannamei* reared in outdoor tanks at a stocking density of 20 shrimp/m^2 and fed commercial feed. After an 11-week culture period, restricting feeding by 40% (or feed 60% of SFP) showed no effects on final weight of this species raised in a tank system continuously receiving the green water from culture ponds. Their research indicated that in semi-intensive ponds, if taken advantage of, the primary productivity can partially satisfy nutritional requirements of shrimp. Therefore, restriction of commercial feed ration will encourage shrimp to forage and consume natural food available within the culture system. In contrast, when the food including artificial and natural food are abundant, there may be occurrence of selection based on appetite and eating habit. Burford et al. (2004) reported that epiphytes constantly contributed to the carbon requirements of post-larval shrimp at the level of 39-53% regardless of the addition of formulated feed *ad libitum*.

The natural productivity is often a good food source and needs to be taken into consideration in feed management. Tacon (2002) noted that although growth and shrimp health are governed by food containing about 40 essential nutrients, the form in which these nutrients are supplied varies by type of farming model and feeding strategy. For instance, extensive shrimp farming systems attain these nutrients mainly from live food organisms within the pond ecosystem; whereas with semi intensive farming system, nutrients are supplied by a combination of natural food organisms and externally supplied feed. In addition to farming system model, shrimp stocking density is also essential in determination of feed type and feed quantity. In SFP:80:90:100, the feed was increased gradually with culture time, the mean final weight (25.8 g) was not significantly smaller than that of SFP (27.2 g). This is similar to the result observed in the tank trial. The amount of feed per shrimp is reduced when the total feed input is restricted. This forces shrimp to utilize the natural food available in pond to meet the nutritional demand. Carvajal-Valdes et al. (2012) conducted an experiment for 84 days in acclimation tanks of farms fertilized periodically at densities of 15, 25 and 35 shrimp/m^2. The authors found that there were no significant differences in weekly growth rate between shrimp fed with 50% reduction in feeding rate and shrimp fed according to the feeding table of food manufacturer. Meanwhile, the FCR greatly improved for treatments reducing 50% feed input compared to treatments fed with full ration: 1.48 vs. 2.71, 1.53 vs. 3.00 and 1.65 vs. 3.27 at stocking densities of 15, 25 and 35 shrimp/m^2, respectively. These show that it is possible to reduce the amount of feed input that have minor reduction on yields but resulting in large cost reductions; meanwhile, extra feeding does not improve results.

The similar response was found for SFP:90 in ponds, but not for T90 in grow-out tanks. Final shrimp weight of SFP:90 (26.1 g) was insignificantly different from SFP (27.2 g); however, the final shrimp weight in tanks was significantly smaller in T90 (10.2 g) than the weight in T100 (11.6 g). Mathematically, the amount of feed reduced in SFP:80:90:100 and SFP:90 in ponds (or T80:90:100 and T90 for tank trial) was equal. However, it is interesting that individual weight is not affected by reducing feed when protocol 80:90:100 is employed either in ponds or tanks. This can be due to the fact that the natural food is depleted gradually towards the end of production cycle as shrimp get bigger. As discussed earlier, it appears that shrimp increasingly consumed artificial feed provided to satisfy nutritional demand, resulting in optimal growth. Morthy and Altaff (2002) analyzed the composition of gut contents of *P. monodon* and found that the percentages of zooplankton decreased from 24.9 to 8.6 % when shrimp weight increased from 2-30 g; the opposite trend was found for pelleted food, increasing from 5.2 - 28.5 % for shrimp sizing from 2-30 g. In contrast, when feed was reduced by 10% throughout the culture period, final weights of shrimp from the ponds were not influenced but final shrimp weights were reduced in the tanks. This can be in part due to difference in density. Stocking density for ponds was 28 shrimp/m^2, meanwhile it was 35 shrimp/m^2 for tanks. Higher stocking density possibly causes more pressure on food scarcity when natural food is not enough to compensate for 10% of feed reduction during the course of culture. Another possible explanation is that the natural food in tanks is less abundant than that in ponds due to designed tank trial only allows partial water exchanged. This may restrict animals to fully access the natural food throughout the course of experiment, causing the inferior growth for shrimp in T90 of tank trial. The assumption that lack of natural food cannot make up the growth for shrimp fed less artificial feed is supported by the research of Roy et al. (2012), the tanks were filled with pond water but designed to culture *L. vannamei* in static system. The authors found that the growth numerically decreased when the feed rations decreased from 100% to 0% in the zero water exchange system.

Although multiple benefits of natural productivity have been reported in shrimp ponds (Anderson et al., 1987; Focken et al., 1998), it is very unlikely to measure exactly to what extent natural food has been exploited by shrimp and what stages shrimp are likely to consume the most natural food. The level that natural productivity is consumed by shrimp can be reduced as the shrimp get bigger; however, it is believed that natural food including detritus and microorganism are continuously taken during the culture time due to the feeding habit (Nunes et al., 1997; Gamboa-delgado et al., 2003, Soares et al., 2005, Roy et al., 2012). Using weekly mean weight data, the quarterly (4-week period) growth rates of the shrimp were determined using Thermal Growth Coefficient (TGC) as this minimizes differences in initial weight. In this trial the TCG of shrimp (Table 7) assigned to the SFP (0.185) was significantly bigger than that of shrimp assigned to the other treatments for the first quarter. Since all feeding protocols were equal during this time, this is likely due to biological variation of pond-based experiment. In the third quarter shrimp maintained on the SFP:80:90:100 received 90% of the feed as compared to the SFP had a significantly smaller TGC. No significant differences were observed for the second quarter and fourth quarter when different feeding allowances were practiced (Table 7). This is probably due to consumption of natural productivity throughout the culture period so that shrimp in SFP:90 and SFP:80:90:100 did not suffer from nutrient insufficiency caused by restricted feed inputs.

The response of shrimp in high density ponds to restricted feeding protocols is quite similar to the response of shrimp in low density ponds (Chapter II). As feed input decreased by 10% from SFP, the biomass decreased from 486 kg (SFP) to 471 kg for SFP:80:90:100 and 463 kg for SFP:90, although these differences were statistically insignificant. In the low density pond trial with 10% difference in feed input, the biomass of SFP (252 kg) was insignificantly bigger than the biomass of SFP:90 (204 kg). Overall, shrimp biomass was not affected by reducing feed input by 10% at a density of 10 and 28 shrimp/m^2 when shrimp had access to natural food. The benefit from restricting feed application is the potential of improving FCR. Although no significant differences are found, the FCRs appeared to be smaller for treatments having less feed input, being 0.99, 0.99 and 1.02 for SFP:80:90:100, SFP:90 and SFP, respectively. Improved FCR by reducing feed application was also reported by da Silva (2013) where shrimp receiving half rations of diet showed an improved FCR of 0.69 in comparison with FCR of 1.24 when shrimp received the full feed rations. This means in culture systems where natural food is available, reducing feed input is economically beneficial due to improving FCR.

When evaluating the economic efficiency, FCR is often an indicator for success because it reflects directly how much feed is provided per unit of weight gain. That is correct but not complete because profit of a farm is based on other factors, such as survival rates and final weight of culture animal. For example, farm-raised animals tend to be larger for ponds that have lower survival or are stocked at lower density. In this case, reduced (or lower) FCR is likely to indicate the high efficiency of feed use, but it is not necessary to be profitable due to the overall production value being reduced because of poor survival and subsequently lower total biomass. Economic efficiency should not be merely evaluated based on FCR performances because a compromise between quantity and quality often occurs for farm-raised animals (high density and smaller sizes vs. low density and larger sizes). Yield is the product of individual weight gain and the number of culture animal harvested. Weight gain is often limited by environmental and genetic factors; stocking at a higher density is the common way to increase the yield per unit area. However, as mentioned earlier there is a negative correlation between stocking density and growth. This has been reported by several researchers (Wyban et al., 1987; Allan and Maguire, 1992; Williams et al., 1996; Araneda et al., 2008). Sookying et al., (2011) demonstrated density-dependent response in which the final shrimp weights after 10-wk-culture period were reduced from 16.1 to 13.6 g and the FCR increased from 1.15 to 1.54 as the density increased from 15 to 65 shrimp/m^2 under green-water tank conditions.

Market price is the driving force for shrimp production. Therefore, outcome expectancy may be important in choosing feeding strategies. If high market price is predicted for larger size classes, it may be worth reducing stocking density to increase profit margin or/and using standard feeding program to produce premium size. In Table 9, the production of count size above 56 - 66 shrimp/kg were 4532, 4787 and 4596 kg/ha (or 97.2, 98.3 and 97.6% presented in Table 8) for SFP:90, SFP and SFP:80:90:100. The detail of size distribution of treatments is shown in Figure 3. The shrimp size greatly contributes to economic success of a farm. For example, in the largest group 24-33 count/kg, Table 10 showed that the gross income generated from the SFP ($5397/ha) was nearly twice that of the SFP:90 ($2920/ha) and SFP:80:90:100 ($3188/ha). The production of the largest size group of SFP was 24.0% but it represented 27.6% of total gross income of SFP. In this study, the feed input was less in restricted feeding programs than in SFP. This lead to significantly reduced feed cost for the former. However, when feed cost per production unit was calculated, no significant differences among feeding protocols was observed. Feed cost was $0.97, $0.99 and $1.02 to produce each kg of shrimp for SFP:80:90:100, SFP:90 and SFP, respectively. As mentioned earlier, the economic return of a farm depends largely on the shrimp size and survival. With similar production (or survival), producing higher percentage of large shrimp resulted in better partial return for SFP ($14645/ha) compared to SFP:90 ($13889/ha) and SFP:80:90:100 ($14070/ha). On the other hand, restricted feed ration also has its advantages, permitting improved FCR at the expense of growth at the same time avoiding the wastage. In this study, it is likely to make more economic sense to choose restricted rations for feeding strategies for two reasons. Firstly, the investment on feed cost for restricted feeding protocol (SFP:80:90:100 and SFP:90) was significantly lower than that for SFP while the partial returns were not significantly different among treatments. In other words, a significant difference in investment did not result in a significant difference in the return. This may cause economic loss for operations that require a loan for shrimp culture because the interest after 4-month production cycle can be higher than the limited return gain of SFP (Table 11). Secondly, the time value of money concept may exaggerate the economic failure for SFP. For example, the difference in feed cost between SFP ($4937) and SFP80:90:100 ($4536) was $401, but after 4 months this gap no longer retained at $401 but was bigger because the value of money theoretically decreased every day. Hence, effective feeding practices require understandings of biological aspects of culture species and economic changes associated with each type of feeding strategies.

5. Conclusion

Mean survival, growth, FCR and economic returns were not affected by restricted feeding protocols (SFP:90 and SFP:80:90:100). Standard feeding protocol showed higher investment in feed but had greater partial return as a result of high percentage of large shrimp. Selection of restricted or full feeding ration to apply in feeding management depends on the financial status and outcome expectancy of each farm. As feed management is critically linked to growth, survival and economic returns more research should focus on evaluation of feed management on production and economic efficiency for this species.

References

Akiyama, D.M., 1993. Semi-extensive shrimp farm management. ASA Technical Bulletin, MITA (P) No. 518/12/92, Vol. AQ 38 1993/3. American Soybean Association, Singapore, 20p.

Allan, G.L., Maguire, G.B., 1991. Lethal levels of low dissolved oxygen and effects of short-term oxygen stress on subsequent growth of juvenile *Penaeus monodon*. Aquaculture 94, 27-37.

Allan, G.L., Maguire, G.B., 1992. Effects of stocking density on production of *Penaeus monodon* Fabricius in model farming ponds. Aquaculture 107, 49-66.

Anderson, R.K., Parker, P.L., Lawrence, A., 1987. A $^{13}C/^{12}C$ trace study of utilization of presented feed by a commercially important shrimp *Penaeus vannamei* in a pond grow-out systems. Journal of the World Aquaculture Society 18, 148-155.

Andrews, J.W., Murai, T., Gibbons, G., 1973. The influence of dissolved oxygen on the growth of catfish. Trans. American Fisheries Society 102, 835-8.

Araneda, M., Pérez, E.P., 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.

Bianchi, M., Bedier, A., Bianchi, A., Domenach, M., Marty, D., 1990. Use of ^{15}N labeled food pellets to estimate the consumption of heterotrophic microbial communities to penaied prawn diet in closed-system aquaculture. Pages 227-230 In: Lesel. R. (Ed.), Proceedings of the Special Session on Shrimp Farming. World Aquaculture Society, Baton Rouge, LA, USA.

Bombeo-Tuburan, I., Guanzon, N.G. Jr., Schroeder, G.L., 1993. Production of *Penaeus monodon* (Fabricius) using four natural food types in an extensive system. Aquaculture 112, 57-65.

Boyd, C.E., Tucker, C., McNevin, A., Bostick, K., Clay, J., 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. Reviews in Fisheries science 15, 327-360.

Bratvold, D., Lu, J., Browd, C.L., 1999. Disinfection, microbial community establishment and shrimp production in a prototype biosecure pond. Journal of the World Aquaculture Society 30, 422-432.

Burford, M.A., Sellars, M.J., Arnold, S.J., Keys, S.J., Crocos, P.G., Preston, N.P., 2004 Contribution of the natural biota associated with substrates to the nutritional requirements of post-larval shrimp (*Penaeus esculentus*) in high-density rearing systems. Aquaculture Research 3, 508-515.

Carvajal-Valdes, R., Arjona, E., Bueno, G., 2012. Feeding rate and stocking density in semi-intensive *Litopenaeus vannamei* culture with moderate periodic fertilization. Journal of Agricultural and Biological Science 7, 899-904.

Carvalho, E.A., Nunes. A.J.P., 2006. Effects of feeding frequency on feed leaching loss and grow-out patterns of the white shrimp *Litopenaeus vannamei* fed under a diurnal feeding regime in pond enclosures. Aquaculture 252, 494-502.

da Silva, F.S.D., 2013. Development and Application of Non Marine Ingredients Based Diets for Pacific White Shrimp, *Litopenaeus vannamei*: Examining the Suitability of Alternative Lipid Sources. Doctoral dissertation, Auburn University, USA.

Davis, D.A., Venero, J.A., 2005. Rethinking feeding for cultured shrimp. Global Aquaculture Advocate 8, 78-81.

Davis, D.A., Amaya, E., Venero, J., Zelaya, O., Rouse, D.B., 2006. A case study on feed management to improve production and economic returns for the semi-intensive pond production of *Litopenaeus vannamei*. Pages 282-303 in: Cruz Suarez, L.E., Maria, D.R., Salazar, M.T., Lopez, M.G.N., Cavazos, D.A.V., Cruz, A.C.P., Ortega, A.G. (Eds.). Avances en nutrición acuícola, VIII. Simposio Internacional de Nutrición Acuícola. [Advances in aquacultural nutrition, VIII. International Symposium on Aquacultural Nutrition.] Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, Mexico.

Davis, D.A., Roy, L.A., Sookying, D., 2008. Improving the cost effectiveness of shrimp feeds. In *Avances en Nutricion Acuicola IX. IX Simposio Internacional de Nutricion Acuicola* (pp. 24-27). Marie, Mireya Tapia Salazar, Martha G. Nieto López, David A. Villarreal Cavazos, Juan Pablo Lazo y Ma. Teresa Viana. Avancese en Nutrición Acuícola IX. IX

SimposioInternacional de NutriciónAcuícola. 24-27 Noviembre. Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, México.

De Silva, S.S., 1989. Reducing feed costs in semi-intensive aquaculture system in the tropics. Naga, The ICLARM Quarterly 12, 6-7.

De Silva, S.S., Hasan, M.R., 2007. Feeds and fertilizers: the key to long term sustainability of Asian aquaculture. In: Hasan, M.R., Hecht, T., De Silva, S.S., Tacon, A.G.J. (Eds.), Study and analysis of feeds and fertilizers for sustainable aquaculture development, pp. 19-47. FAO Fisheries Technical Paper No. 497. Rome, FAO. 510 pp.

FAO., 2010. Report of the FAO Expert Workshop on on-farm feeding and feed management in aquaculture. Manila, the Philippines, 13-15 September 2010. FAO Fisheries and Aquaculture Report No. 949. Rome, FAO. 37 pp.

FAO., 2012. Fishstat Plus, Vers. 2.32. Rome, FAO. (available at www.fao.org/fishery/statistics/software/fishstat/en)

FAO., 2014. The State of World Fisheries and Aquaculture 2014. Rome. 223 pp.

Focken, U., Groth, A., Coloso, R.M., Becker, K., 1998. Contribution of natural food and supplemental feed to the gut content of *Penaeus monodon* Fabricius in a semi-intensive pond system in the Philippines. Aquaculture 164, 105-116.

Fox, J., Treece, G.D., Sanchez, D., 2001. Shrimp nutrition and feed management. Pages 65-90 in: Haws, M.C; Boyd, C.E. (Eds.), Methods for improving shrimp farming in Central America. University of Central America Press, Managua, Nicaragua.

Gamboa-delgado, J., Molina-poveda, C., Chantal, C., 2003. Digestive enzyme activity and food ingesta in juvenile shrimp *Litopenaeus vannamei* (Boone, 1931) as a function of body weight. Aquaculture research 34, 1403-1411.

Garza, A., 2001. Influence of nursery and feed management on pond production of *Litopenaeus vannamei*. Master's thesis. Auburn University, Auburn, Alabama, USA.

Goddard, S., 1996. Feed management in intensive aquaculture. Chapman Hall, New York, NY USA.

Grow, D.J., Loizides, L., Nott., J., 1978. Satiation amount, frequency of feeding and gastric emptying rate in *Salmo gairdneri*. Journal of Fish Biology 12, 507-516.

Hepher, B., 1998. Nutrition of pond fishes. Cambridge University Press, Cambridge.

Kueshy, N., Davis, D.A., 2002. Protein requirement for maintenance and maximum weight gain for the Pacific White shrimp, *Litopenaeus vannamei*. Aquaculture 204, 125-143.

Lawrence, A.L., Lee, P.G., 1997. Research in the Americas. In: D'Abramo, L.R., Conklin, D.E., Akiyama, D.M. (Eds.), Crustacean Nutrition. Advances in World Aquaculture, Vo1.6. World Aquaculture Society, Baton Rouge, pp.566 - 587

Mohanty, R.K., 2001. Feeding management and waste production in semi-intensive farming of *penaeus monodon* (fab.) at different stocking densities. Aquaculture International 9, 345-355.

Moorthy, M.S., Altaff, K., 2002. Role of natural productivity in modified extensive shrimp pond growing *Penaeus monodon* (penaeidae, crustacea). Indian Journal of Marine Sciences 31, 195-200.

Morales, A.E., Cardenete, G., de la Higuera, M., Sanz, A., 1994. Effects of dietary protein source on growth, feed conversion and energy utilization in rainbow trout, *Oncorhynchus mykiss*. Aquaculture 124, 117-126.

Moss, S.M., Pruder, G.D., 1995. Characterization of organic particle associated with rapid growth in juvenile white shrimp, *Penaeus vannamei* Boone, reared under intensive culture conditions. Journal of Experimental Marine Biology and Ecology 187, 175-191.

Nunes, A.J.P., Parsons, G.J., 2000. Size-related feeding and gastric evacuation measurements for the Southern brown shrimp *Penaeus subtilis*. Aquaculture 187, 133-151.

Nunes, A.J.P., Gesteira, T.C.V., Goddard, S., 1997. Food ingestion and assimilation by the Southern brown shrimp *Penaeus subtilis* under semi-intensive culture in NE Brazil. Aquaculture 149, 121-136.

Patanaik, S., Samocha, T.M., 2009. Improved feed management strategy for *Litopenaeus vannamei* in limited exchange culture systems. World Aquaculture 40, 57-59.

Ponce-Palafox, J., Martinez-Palcacios, A., 1997. The effects of salinity and temperature on the growth and survival rates of juveniles white shrimp, *Penaeus vannamei*, Boone, 1931. Aquaculture 157, 107-115.

Roy, L.A., Davis, D.A., Whitis, G.N., 2012. Effect of feeding rate and pond primary Productivity on growth of *Litopenaeus vannam*ei reared in inland saline waters of West Alabama, North American Journal of Aquaculture 74, 20-26.

Sedgwick, R.W., 1979. Effect of ration size and feeding frequency on the growth and food conversion of juvenile *Penaeus merguiensis*. Aquaculture 16, 279-298.

Shipton, T.A., Hasan, M.R., 2013. An overview of the current status of feed management practices. In: Hasan, M.R., New, M.B. (Eds.), On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. pp. 3–20.

Soares, R., Peixoto, S., Wasielesky, W., D'Incao., F., 2005. Feeding rhythms and diet of *Farfantepenaeus paulensis* under pen culture in Patos Lagoon estuary. Brazil Journal of Experimental Marine Biology and Ecology 322, 167-176.

Tacon, A.G.J., 2000. Production of feeds for aquatic organisms in tropics with particular reference to Latin America and Caribbean. In: Cyrino, J.E., Moura, J.C., Caseiro. A.C., Sampaio, A.M.B. (Eds.), Proceedings - VIII Simpósio Brasiliero de Aqüicultura, Fundaçao de Estudos Agrários Luiz de Queiroz, Piracicaba, SP, Brasil. pp. 17-31.

Tacon, A.G.J., 2002. Thematic Review of Feeds and Feed Management Practices in Shrimp Aquaculture. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 69 pages.

Tacon, A.G.J., Hasan, M.R., Allan, G., El-Sayed, A.F.M., Jackson, A., Kaushik, S.J., Suresh, W.K.Ng,V., Viana, M.T., 2012. Aquaculture feeds: addressing the long-term sustainability of the sector in Subasinghe, R.P., Arthur, J.R., Bartley, D.M., De Silva, S.S., Halwart, M., Hishamunda, N., Mohan, C.V., Sorgeloos, P. (Eds), Farming the water for people and food. Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22-25 September 2010. Pp. 193-231. FAO, Rome and NACA, Bangkok.

Trino, A., Sarroza, J., 1995. Effect of a diet lacking in vitamin and mineral supplements on growth and survival of *Penaeus monodon* juveniles in a modified extensive culture system. Aquaculture 136, 323-330.

Velasco, M., Lawrence, A.L., Castille, F.L., Obaldo, L.G., 2000. Determining optimal dietary protein level for *Litopenaeus vannamei* postlarvae. The Global Aquaculture Advocate 3, 46-47.

Williams, A.S., Davis, D.A., Arnold, C.R., 1996. Density-dependent growth and survival of *Penaeus setiferus* and *Penaeus vannamei* in a semi-closed recirculating system. Journal of the World Aquaculture Society 27, 107-112.

Williams, S., 1984. Official methods of analysis of the Association of Official Analytical Chemists.

Wyban, J.A., Lee, C.S., Sato, V.T., Seeney, J.N., Richards, W.K., 1987. Effects of stocking density on shrimp growth rates in manure-fertilized ponds. Aquaculture 61, 23-32.

Wyban, J.A., Sweeney, J.N., 1991. Intensive shrimp production technology. The Oceanic Institute, Honolulu, Haiwaii, USA.

Wyban, J., Walsh, W.A., Godin, D.M., 1995. Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp (*Penaeus vannamei*). Aquaculture 138, 267-279.

Zeigler, T.R., 2014. Why do we feed shrimp the way we do? Global Aquaculture Advocate 5, 28-30.

Zelaya, O., 2005. An evaluation of nursery techniques and feed management during culture of marine shrimp *Litopenaeus vannamei*. Doctoral dissertation. Auburn University, Auburn, Alabama, USA.

Table 1 Six treatments designed to test effects of feeding protocols on growth performance *of L vannamei* in green water tanks for 6-week culture period.

Treatment	Week					
	1	2	3	4	5	6
80:90:100	80		90		100	
90:100	90			100		
100	100					
100:110	100			110		
110	110					

Table 2 Summary of water quality fluctuations observed over the 6-week culture period of *L.vannamei*, fed different feeding ratios in green water tanks. The values are shown in mean ± standard deviation and minimum to maximum values in parenthesis.

	Temperature (^{0}C)	DO[a] (mg L^{-1})	pH	Salinity (ppt)	TAN[b] (mg L^{-1})
am	26.73 ± 1.11 (23.70, 28.8)	7.17 ± 0.27 (6.40, 7.91)	7.90 ± 0.25 (8.31, 7.03)	3.75 ± 1.67 (2.50, 7.75)	0.16 ± 0.15 (0.00, 0.4)
pm	29.40 ± 1.38 (25.80, 32.00)	6.80 ± 0.38 (6.02, 7.58)	8.12 ± 0.38 (6.41, 8.74)	3.77 ± 1.71 (1.27, 7.85)	

[a] Dissolved oxygen

[b] Total ammonia-nitrogen

Table 3 Responses of Pacific white shrimp (initial mean weight ± SD; 0.76 ± 0.07 g) to varying feed rations over a 6-week growth trial in outdoor tanks.

Treatment[1]	Final Weight (g)	Percent Wt.Gain (%)	Weekly Wt. Gain (g)	Final Biomass (g)	Survival (%)	FCR[2]	Feed cost/kg shrimp (usd/kg)
80:90:100	11.4[a]	1423	1.78[ab]	334[ab]	97.5	0.76	1.14[b]
90	10.2[b]	1307	1.58[b]	298[b]	97.5	0.85	1.29[ab]
90:100	10.9[ab]	1306	1.68[ab]	317[ab]	97.5	0.84	1.28[ab]
100	11.6[a]	1459	1.81[a]	334[ab]	95.8	0.84	1.28[ab]
100:110	11.5[a]	1355	1.79[ab]	342[a]	99.2	0.86	1.30[ab]
110	11.9[a]	1424	1.86[a]	354[a]	99.2	0.87	1.32[a]
P value	0.0167	0.659	0.0199	0.0188	0.4613	0.1150	0.0369
PSE[3]	0.0382	80.4374	0.0539	10.3875	1.2729	0.0265	0.0375

[1]: Treatment with 3 values represented 2-week interval, 2 values indicated 3-week interval and value expressed for 6-week interval.

[2]FCR: Feed Conversion Ratio.

[3]PSE: Pooled Standard Error

Table 4 Dry matter, protein and energy of whole body shrimp after 6-week culture fed different feeding rations in green water tanks.

Treatment	Dry matter (%)	Protein (%)	Energy (Kcal/g)
80:90:100	24.1	68.1	4693
90	23.3	67.8	4718
100:90	24.1	68.5	4757
100	24.1	67.1	4658
110:110	24.4	66.8	4743
110	24.5	66.7	4647
p-value	0.7064	0.8763	0.448
PSE[1]	0.3812	1.6393	50.4953

[1]Pooled standard error.

Figure 1a Feed input (g) at the end of 6-week trial regressed against mean final weight (g).

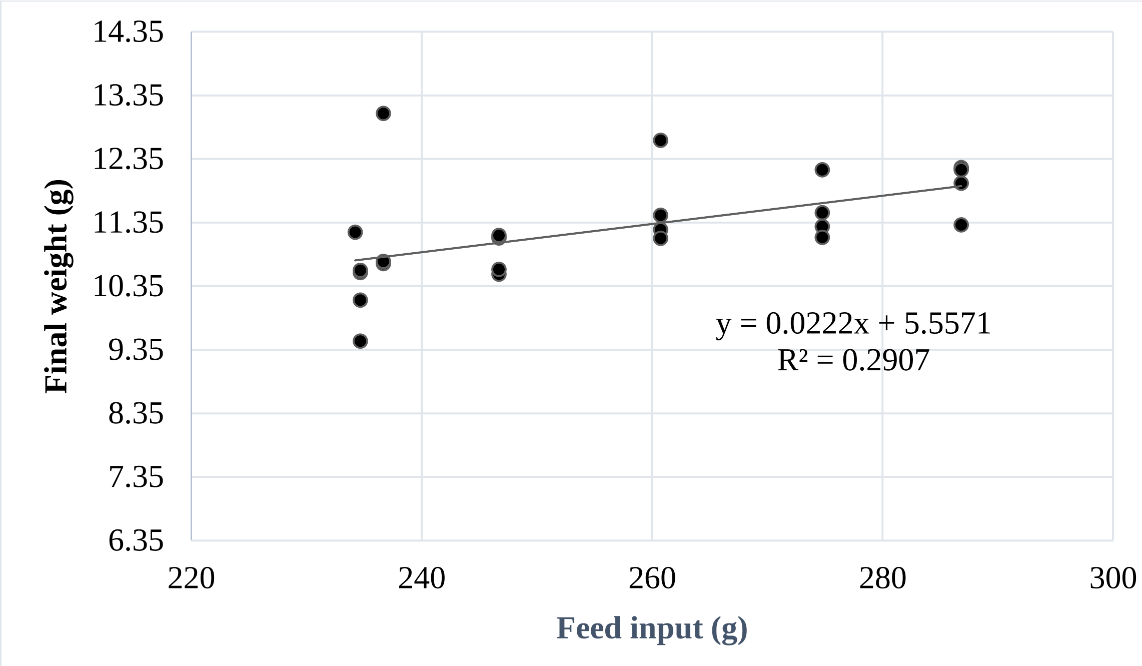


Figure 1b Feed input (g) of T90, T100 and T110 at the end of 6-week trial regressed against mean final weight (g).

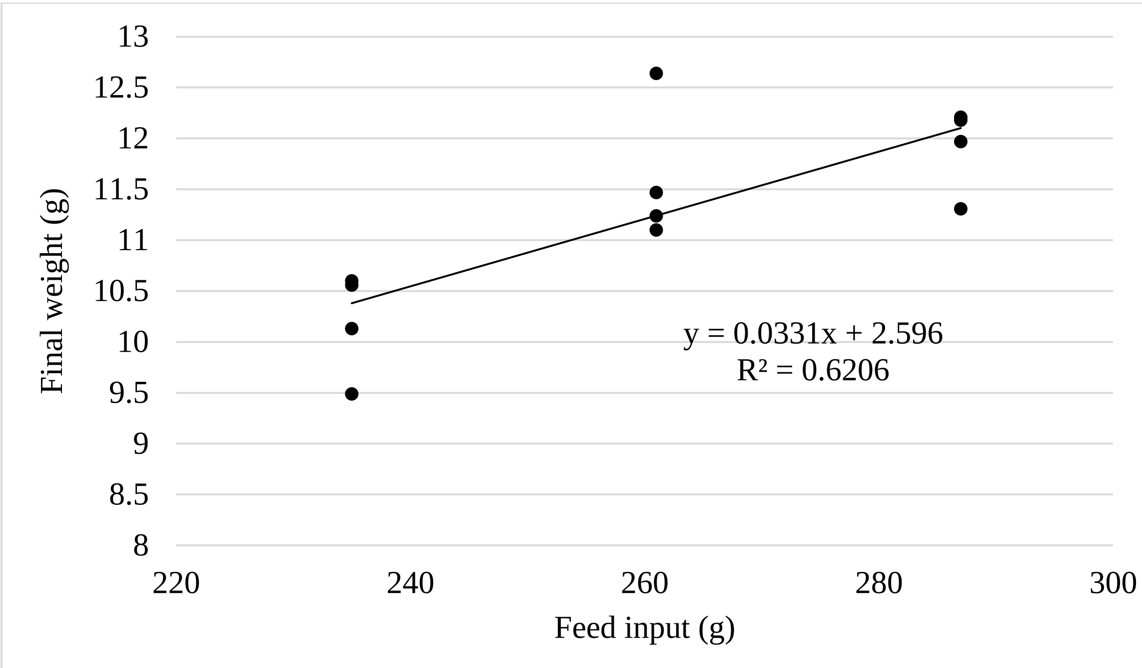


Table 5 Summary of water quality parameters observed over the 16-week culture period of *L. vannamei*, fed three feeding protocols in 0.1-ha ponds. The values are shown in mean ± standard deviation and minimum to maximum values in parenthesis.

Parameter	**SFP:90**	**SFP**	**SFP:80:90:100**
Temperature (°C)			
am	29.46 ± 1.37	29.75 ± 1.30	29.60 ± 1.28
	(21.70, 31.50)	(22.70, 32.00)	(23.20, 31.70)
noon	31.69 ± 1.67	31.85 ± 1.64	32.12 ± 1.73
	(26.60, 35.30)	(26.40, 35.10)	(26.80, 35.90)
pm	31.79 ± 1.59	31.99 ± 1.58	32.23 ± 1.69
	(26.60, 34.30)	(27.10, 34.70)	(27.10, 35.30)
DO[a] (mg L^{-1})			
am	4.45 ± 0.87	4.41 ± 1.07	4.26 ± 0.85
	(2.35, 7.76)	(1.52, 9.48)	(1.72, 7.99)
noon	10.60 ± 2.56	10.82 ± 2.74	10.86 ± 2.87
	(4.46, 18.41)	(2.21, 19.86)	(4.83, 19.94)
pm	9.90 ± 2.76	10.13 ± 2.80	10.02 ± 2.76
	(1.77, 21.59)	(2.60, 20.78)	(2.56, 19.80)
pH			
am	7.85 ± 0.42	7.87 ± 0.49	7.75 ± 0.27
	(6.95, 9.28)	(7.22, 9.15)	(7.05, 8.67)
noon	8.66 ± 0.49	8.89 ± 0.50	8.80 ± 0.50
	(7.49, 10.09)	(7.32, 10.05)	(6.36, 10.09)
pm	8.83 ± 0.47	8.88 ± 0.47	8.78 ± 0.44
	(7.51, 9.89)	(7.33, 10.16)	(7.33, 10.03)
Salinity (ppt)			
am	10.98 ± 1.19	11.28 ± 1.20	10.90 ± 1.36
	(845, 10.86)	(8.43, 14.48)	(7.27, 14.09)
noon	10.92 ± 1.17	11.22 ± 1.19	11.07 ± 1.33
	(8.46, 13.89)	(8.44, 14.44)	(4.83, 19.94)
pm	10.91 ± 1.16	11.21 ± 1.19	11.08 ± 1.32
	(8.45, 13.60)	(8.47, 14.45)	(7.75, 14.09)
Secchi (cm)	45.99 ± 33.87	54.01 ± 38.00	45.43 ± 31.59
	(10, 135)	(10, 150)	(10, 120)
TAN[b] (mg L^{-1})	0.19 ± 0.50	0.28 ± 0.94	0.09 ± 0.31
	(0.00, 3.00)	(0.00, 6.00)	(0.00, 2.00)

[a] Dissolved oxygen
[b] Total ammonia-nitrogen

Table 6 Mean production parameters of juvenile Pacific white shrimp, *L. vannamei* (228 mg mean initial weight), fed three feeding rations after a 16-week growth trial in 0.1-ha ponds.

Treatment	Yield (kg/ha)	Biomass (kg)	Final weight (g)	Weekly weight gain (g)	Survival (%)	FCR[1]
SFP:90	4664	463	26.1	1.63	63.4	0.99
SFP	4869	486	27.2	1.70	63.9	1.02
SFP:80:90:100	4710	471	25.8	1.61	65.2	0.99
P-value	0.7102	0.6520	0.5293	0.5626	0.7808	0.5657
PSE[2]	178.6892	17.9081	0.89074	0.055811	1.67060	0.03353

[1]FCR: Feed Conversion Ratio

[2] Pooled standard error.

One pond was excluded from treatment SFP:80:90:100 (n=3) due to power failure at midnight before harvest one week.

Table 7 Thermal Grow coefficient of *L.vannamei* fed three feeding rates in ponds over 16 week culture.

Quarter	SFP:90	SFP	SFP:80:90:100	P-value	PSE
Q1 (wk 0 – wk 4)	0.161[a]	0.185[b]	0.160[a]	0.0030	0.0038
Q2 (wk 4 – wk 8)	0.059	0.071	0.061	0.3279	0.0052
Q3 (wk 8 – wk 12)	0.037[cd]	0.041[d]	0.031[c]	0.0225	0.00003
Q4 (wk 12- wk 16)	0.024	0.017	0.025	0.1715	0.00004

[1]Pooled standard error.

Table 8 Population percentage of count size 56-66 shrimp/kg and up of *L.vannamei* fed three different feeding protocols after 16 weeks and the percentage of shrimp count 56-66 shrimp/kg above.

Treatment	Yield (kg/ha)	Above 56-66/kg (kg/ha)	Above 56-66/kg (%)
SFP:90	4664	4532	97.2
SFP	4869	4787	98.3
SFP:80:90:100	4710	4596	97.6
P-value	0.64		
PSE	174.9029		

[1]Pooled standard error.

Table 9 Production per count size for three treatments. The price is used based on the publication of Sookying (2011).

Count shrimp/kg	Kg for each class size			Price ($/kg)
	SFP:90	SFP	SFP:80:90:100	
24-33	664	1227	724	4.4
34-43	3209	3037	3034	4.0
44-55	560	434	718	3.6
56-66	100	81	119	3.5
67-77	79	40	53	3.4
78-88	30	42	31	3.3
89-110	15	0	30	3.1
111-133	8	8	0	2.6

Table 10 Gross income of *L. vannamei* raised in ponds after 16-week culture under three feeding protocols.

	Gross income (USD)		
Shrimp (count/kg)	SFP:90	SFP	SFP:80:90:100
24-33	2920	5397	3188
34-43	12706	12027	12017
44-55	2032	1575	2605
56-66	351	287	419
67-77	268	136	182
78-88	99	139	104
89-110	46	0	92
111-113	22	21	0
Total ($/ha)	18,444	19,582	18,607

Table 11 Economic evaluation of *L.vannamei* cultured in ponds under different feeding protocols after 16 week culture.

Treatment	Production Value ($/ha)	Feed Cost ($/ha)	Feed cost/kg shrimp (USD)	Partial return (USD)
SFP:90	18444	4555	0.98	13889
SFP	19581	4937	1.02	14645
SFP80:90:100	18606	4536	0.97	14070
P-value	0.6520		0.7040	0.8324
PSE[1]	90.3115		0.037375	90.56935

[1]Pooled standard error.

Table 12 Dry matter, protein and energy of whole body shrimp after 16-week culture fed three different feeding rates in ponds.

Treatments	Dry matter (%)	Protein (%)	Energy (kcal/g)
SFP:90	24.8	64.4	4585
SFP	25.0	63.5	4639
SFP:80:90:100	25.3	64.7	4687
P-value	0.7064	0.8763	0.4477
PSE	0.3812	1.6393	50.4953

[1]Pooled standard error.

Figure 2 Feed input of three treatments over 16-week culture

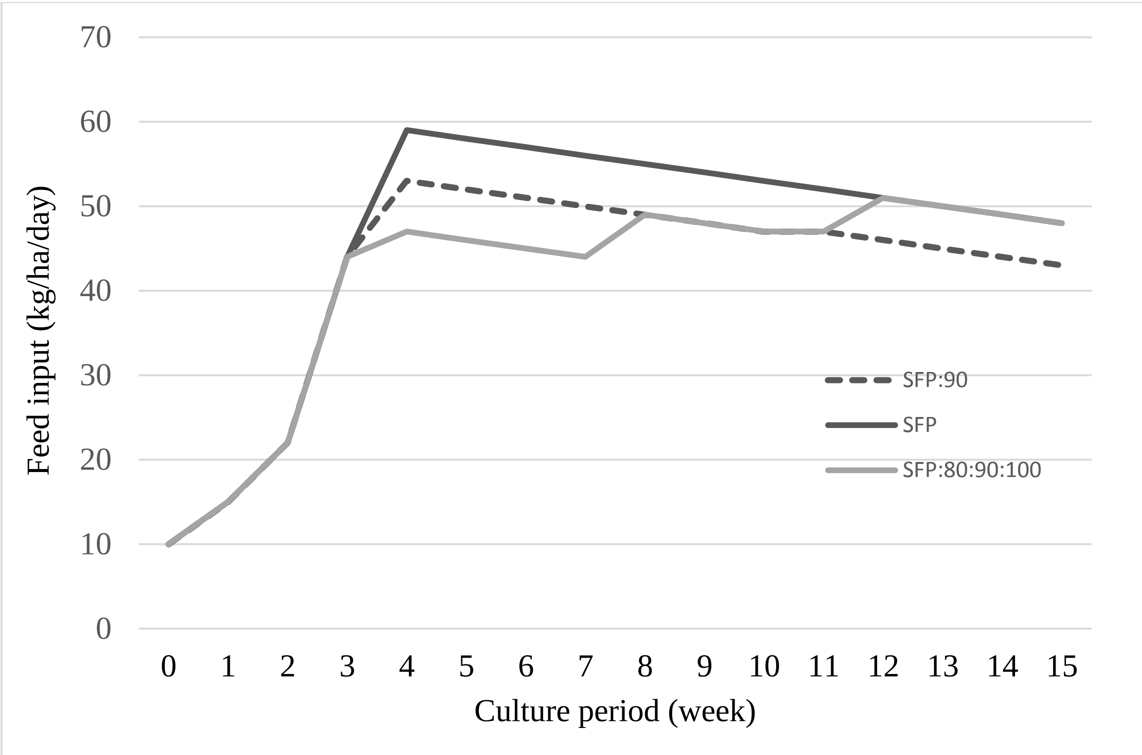
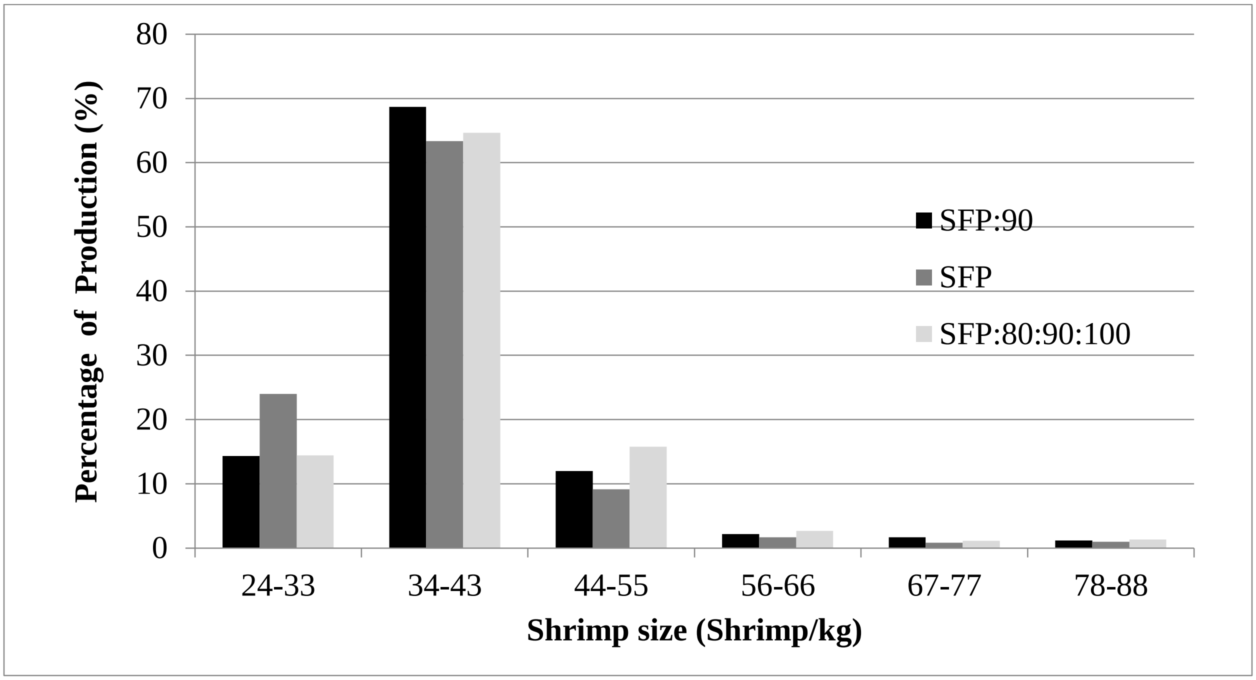


Figure 3 Shrimp size distribution in count/kg with head on after 16-week pond production trial of *L.vannamei*, fed different feeding rations.



CHAPTER IV
SUMMARY AND CONCLUSION

Increasing demand of seafood consumption has encouraged expansion of shrimp aquaculture. Commercial feed use is predicted to continue to increase due to farm intensification. Greater awareness of economic, sustainable and environmental problems of using shrimp feed draw concentration on reducing reliance on costly ingredients in shrimp diet and optimizing feed use. A shrimp production system that is cost-effective and environmentally-sustainable is greatly favored. The research was conducted to refine the current feed management practice and evaluate different feeding schemes, exploring the potential of producing shrimp that are economically profitable and environmentally favorable. The findings in this research have contributed to comprehension of adoption of feeding strategies to improve production and economic performance of *L.vannmei* raised in semi-intensive ponds.

The implementation of standard feeding protocol in shrimp ponds at the stocking density of 10 shrimp/m^2 in Chapter II showed higher partial return by the reason of superior shrimp growth. 10% increase in commercial feed input was not cost effective at the low density in which shrimp were unlikely to have competition to access the natural food. In contrast, feed cost appeared to reduce significantly after reducing feed ration by 10% from standard feed ration, but it did not indicate cost-effectiveness as reduced feed ration restricted maximum growth of animal.

Reduction of feed input may be economically and environmentally beneficial but it is important to note that there are various ways to reduce the same amount of feed input and the response of shrimp to the same restricted feed rate at different densities may be not consistent. From the growth response and economic results observed in the low density pond trial, feeding programs were continually evaluated at densities of 35 and 28 shrimp/m^2 in outdoor water tanks and ponds, respectively. The results in tank trial supported the previous findings in Chapter II - common expectation of improving growth performance by increasing feed input was proved to be unjustified. No significant improvement in growth was found by increasing 10% feed ration; meanwhile, feed cost per production unit was significantly increased. Conversely, 10% reduction of feed input did not negatively influence the shrimp growth resulting in FCR and economic improvement when protocol 80:90:100 was used. The findings of pond trial in Chapter III confirmed that reducing feed allowance by 10% (SFP:90 and SFP:80:90:100) was possible to reduce the feed cost although at some expense on growth. However, better economic return was observed in the treatment receiving the full feed ration. This was due to higher percentage of larger shrimp generating greater partial return for standard feeding protocol. The studies conclude that increase of feed input by 10% in semi-intensive farm (at the density of 10 and 28 shrimp/m^2) did not enhance the shrimp growth and cost efficiency. Hence, it is not recommended to increase the feed in shrimp ponds that have abundant natural productivity. On the other hand, feed input can be either applied at a standard ration to optimize growth and increase economic return or at restricted rations to reduce FCR albeit at the loss of some growth. Adoption of restricted or standard feeding protocols in practical feed management depends on financial status and outcome expectancy of each farm.

LITERATURE CITED

Achupallas, J.M., Zhou, Y., Davis, D.A., 2015. Pond production of Pacific white shrimp, *Litopenaeus vannamei* fed grain distillers dried yeast. Aquaculture Nutrition. doi: 10.1111/anu.12359

Akiyama, D.M., 1993. Semi-extensive shrimp farm management. ASA Technical Bulletin, MITA (P) No. 518/12/92, Vol. AQ 38 1993/3. American Soybean Association, Singapore, 20p.

Allan, G.L., Maguire, G.B., 1991. Lethal levels of low dissolved oxygen and effects of short-term oxygen stress on subsequent growth of juvenile *Penaeus monodon*. Aquaculture 94, 27-37.

Allan, G.L., Maguire, G.B., 1992. Effects of stocking density on production of *Penaeus monodon* Fabricius in model farming ponds. Aquaculture 107, 49-66.

Anderson, R.K., Parker, P.L., Lawrence, A., 1987. A $^{13}C/^{12}C$ trace study of utilization of presented feed by a commercially important shrimp *Penaeus vannamei* in a pond grow-out systems. Journal of the World Aquaculture Society 18:148-155.

Andrews, J.W., Murai, T., Gibbons, G., 1973. The influence of dissolved oxygen on the growth of catfish. Trans. American Fisheries Society, 102, 835-8.

Araneda, M., Pérez, E.P., 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.

Avnimelech, Y., Ritvo, G., 2003. Shrimp and fish pond soils: processes and management. Aquaculture 220, 549-567.

Bianchi, M., Bedier, A., Bianchi, A., Domenach, M., Marty, D., 1990. Use of 15N labeled food pellets to estimate the consumption of heterotrophic microbial communities to penaied prawn diet in closed-system aquaculture. Pages 227-230 In: Lesel. R. (Ed.), Proceedings of the Special Session on Shrimp Farming. World Aquaculture Society, Baton Rouge, LA, USA.

Bombeo-Tuburan, I., Guanzon, N.G. Jr., Schroeder, G.L., 1993. Production of Penaeus monodon (Fabricius) using four natural food types in an extensive system. Aquaculture 112, 57-65.

Boyd, C.E., Lim, C., Queiroz, J., Salie, K., De Wet, L., McNevin, A., 2008. Best management practices for responsible aquaculture. Page 47 in USAID/Aquaculture Collaborative Research Support Program, Corvallis, Oregon State University, Oregon.

Boyd, C.E., Tucker C.S., 1998. Pond aquaculture water quality management. Kluwer Academics Publisher, Boston, Massachusetts, USA.

Boyd, C.E., Tucker, C., McNevin, A., Bostick, K., Clay, J., 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. Reviews in Fisheries science 15, 327-360.

Bratvold, D., Lu, J., Browd, C.L., 1999. Disinfection, microbial community establishment and shrimp production in a prototype biosecure pond. Journal of the World Aquaculture Society 30, 422-432.

Burford, M.A., Sellars, M.J., Arnold, S.J., Keys, S.J., Crocos, P.G., Preston, N.P., 2004 Contribution of the natural biota associated with substrates to the nutritional requirements of post-larval shrimp (*Penaeus esculentus*) in high-density rearing systems. Aquaculture Research 3, 508-515.

Burford, M.A., Williams, K.C., 2001. The fate of nitrogenous waste from shrimp feeding. Aquaculture 198, 79-93.

Carvajal-Valdes, R., Arjona, E., Bueno, G., 2012. Feeding rate and stocking density in semi-intensive *Litopenaeus vannamei* culture with moderate periodic fertilization. Journal of Agricultural and Biological Science 7, 899-904.

Carvalho, E.A., Nunes. A.J.P., 2006. Effects of feeding frequency on feed leaching loss and grow-out patterns of the white shrimp *Litopenaeus vannamei* fed under a diurnal feeding regime in pond enclosures. Aquaculture 252, 494-502.

Charatchakool, P., Turnbull, J.F., Funge-Smith, S., Limsuwan, C., 1994. Health management in shrimp ponds. Aquatic animal health research institute. Department of Fisheries. Kasetsart University, Bangkok, Thailand.

Cockcroft, A., Mclachlan, A., 1986. Food and feeding habits of the surf zone penaeid Prawn *Macropetasma africanus* (Balss). Marine Ecology 7, 345-357.

Cole, B.A., Boyd, C.E., 1986. Feeding rate, water quality, and channel catfish production in ponds. The Progressive Fish-Culturist 48, 25-29.

da Silva, F.S.D., 2013. Development and Application of Non Marine Ingredients Based Diets for Pacific White Shrimp, *Litopenaeus vannamei*: Examining the Suitability of Alternative Lipid Sources. Doctoral dissertation, Auburn University, USA.

Davis, D. A., Venero, J.A., 2005. Rethinking feeding for cultured shrimp. Global Aquaculture Advocate 8, 78-81.

Davis, D.A., Amaya, E., Venero, J., Zelaya, O., Rouse, D.B., 2006. A case study on feed management to improve production and economic returns for the semi-intensive pond production of *Litopenaeus vannamei*. Pages 282-303 in: Cruz Suarez, L.E., Maria, D.R., Salazar, M.T., Lopez, M.G.N., Cavazos, D.A.V., Cruz, A.C.P., Ortega, A.G. (Eds.), Avances en nutriciónacuícola, VIII. Simposio Internacional de Nutrición Acuícola. [Advances in aquaculture nutrition, VIII. International Symposium on Aquaculture Nutrition.] Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, Mexico.

Davis, D.A., Arnold, C.R., 2000. Replacement of fish meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture 185, 291–298.

Davis, D.A., Roy, L.A., Sookying, D., 2008. Improving the cost effectiveness of shrimp feeds. In *Avances en Nutricion Acuicola IX. IX Simposio Internacional de Nutricion Acuicola* (pp. 24-27). Marie, Mireya Tapia Salazar, Martha G. Nieto López, David A. Villarreal Cavazos,Juan Pablo Lazo y Ma. Teresa Viana. Avancesenm NutriciónAcuícola IX. IX Simposio Internacional de Nutrición Acuícola. 24-27 Noviembre. Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, México.

Davis, D.A., Samocha, T.M., Bullis, R.A., Patnaik, S., Browdy, C., Stokes, A., Atwood, H., 2004. Practical diets for *Litopenaeus vannamei* (Boone. 1931): working towards organic and/or all plant production diets. Avances en Nutricion Acuicola VII. Memorias del VII Simposium Internacional de Nutricion Acuicola. 16-19 Noviembre, 2004. Hermosillo, Sonora, Mexico.

De Silva, S.S., 1989. Reducing feed costs in semi-intensive aquaculture system in the tropics. Naga, The ICLARM Quarterly 12, 6-7.

De Silva, S.S., Hasan, M.R., 2007. Feeds and fertilizers: the key to long term sustainability of Asian aquaculture. In Hasan, M.R., Hecht, T., De Silva, S.S., Tacon, A.G.J. (Eds.), Study and analysis of feeds and fertilizers for sustainable aquaculture development, pp. 19–47. FAO Fisheries Technical Paper No. 497. Rome, FAO. 510 pp.

Deutsch, A., Graslund, S., Folke, C., Troell, M., Huitric, M., Kautsky, N., Lebel, L., 2007. Feeding aquaculture growth through globalization. Exploitation of marine ecosystems for fishmeal. Global Environmental Change 17, 238-249.

FAO., 2010. Report of the FAO Expert Workshop on on-farm feeding and feed management in aquaculture. Manila, the Philippines, 13-15 September 2010. FAO Fisheries and Aquaculture Report No. 949. Rome, FAO. 37 pp.

FAO., 2012. Fishstat Plus, Vers. 2.32. Rome, FAO. (available at www.fao.org/fishery/statistics/software/fishstat/en)

FAO., 2014. The State of World Fisheries and Aquaculture 2014. Rome. 223 pp.

Focken, U., Groth, A., Coloso, R.M., Becker, K., 1998. Contribution of natural food and supplemental feed to the gut content of *Penaeus monodon* Fabricius in a semi-intensive pond system in the Philippines. Aquaculture 164, 105-116.

Fox, J., Treece, G.D., Sanchez, D., 2001. Shrimp nutrition and feed management. Pages 65-90 in: Haws, M.C., Boyd, C.E. (Eds.), Methods for improving shrimp farming in Central America. University of Central America Press, Managua, Nicaragua.

Gamboa-Delgado, J., 2013. Nutritional role of natural productivity and formulated feed in semi-intensive shrimp farming as indicated by natural stable isotopes. Aquaculture 6, 36-47.

Gamboa-Delgado, J., Le Vay, L., 2009. Natural stable isotopes as indicators of the relative contribution of soy protein and fish meal to tissue growth in Pacific white shrimp (*Litopenaeus vannamei*) fed compound diets. Aquaculture 291, 115-123.

Gamboa-Delgado, J., Molina-Poveda, C., Cahu, C., 2003. Digestive enzyme activity and food ingesta in juvenile shrimp *Litopenaeus vannamei* (Boone 1931) as a function of body weight. Aquaculture Research 34, 1403-1411.

Garza, A., 2001. Influence of nursery and feed management on pond production of *Litopenaeus vannamei*. Master's thesis. Auburn University, Auburn, Alabama, USA.

Goddard, S., 1996. Feed management in intensive aquaculture. Chapman Hall, New York, NY USA.

Grow, D.J., Loizides, L., Nott, J., 1978. Satiation amount, frequency of feeding and gastric emptying rate in *Salmo gairdneri*. Journal of Fish Biology 12, 507-516.

Guillaume, J., 1997. Protein and amino acids. D'Abramo, L.R., Conklin, D.E., Akiyama, D.M. (Eds.), Crustacean Nutrition, Advance. World Aquaculture Vol. 6, World Aquaculture Society, Baton Rouge, LA, USA (1997), pp. 26-50.

Hepher, B., 1998. Nutrition of pond fishes. Cambridge University Press, Cambridge.

Hertrampf, J.W., Piedal-Pascual, F., 2000. Handbook on Ingredients for Aquaculture Feeds. Kluwer Academic Publishers, Dordrecht, The Netherlands. 573 pp.

Hopkins, J.S., Stokes, A.D., Browdy, C.L., Sandifer, P.A., 1991. The relationship between feeding rate, paddlewheel aeration rate and expected dawn dissolved oxygen in intensive shrimp ponds. Aquaculture Engineering 10, 281-290.

Jolly, C.M., Clonts, H.A., 1993. Economics of Aquaculture. Food Products Press (The Haworth Press), Binghamton, New York, USA.

Jory, D.E. 1995. Feed management practices for a healthy pond environment. Pages 118-143 in: Browdy, C.L., Hopkins, J.S. (Eds.), Swimming through troubled water, proceedings of the special session on shrimp farming. World Aquaculture Society, Baton Rouge, LA, USA.

Jory, D.E., Cabrera, T.R., Dugger, D.M, Fegan, D., Lee, P.G., Lawrence, A.L., Jackson, C.J., McIntosh, R.P., Castaneda, J., 2001. Perspectives on the application of closed shrimp culture systems. Pages 104-152 in: Browdy, C.L., Jory, D.E (Eds.), The New Wave, Proceedings of the special session on sustainable Shrimp culture, Aquaculture. 2001. The World Aquaculture Society, Baton Rouge, Louisiana Orlando, USA.

Kaushik, S.J., 2000. Feeding allowance and feeding practices. In: Basurco, B. (Ed.), Recent advances in Mediterranean aquaculture finfish species diversification. Proceedings of the Seminar of the CIHEAM Network on Technology of Aquaculture in the Mediterranean (TECAM). Cahiers Options Mediterranean 47, 53-59.

Kueshy, N., Davis, D.A., 2002. Protein requirement for maintenance and maximum weight gain for the Pacific White shrimp, *Litopenaeus vannamei*. Aquaculture 204, 125-143.

Lawrence A, L., Lee, P.G., 1997. Research in the Americas. In: D'Abramo L.R., Conklin, D.E., Akiyama D.M. (Eds.), Crustacean Nutrition. Advances in World Aquaculture, Vo1.6. World Aquaculture Society, Baton Rouge, pp.566-587.

Lim, C., Dominy, W., 1990. Evaluation of soybean meal as a replacement for marine animal protein in diets for shrimp (*Penaeu svannamei*). Aquaculture 87, 53-63.

Lovell, T., 1998. Nutrition and Feeding of Fish. Kluwer Academic Publishers, Norwell, Massachusetts.

Martinez-Cordova, L.R., Porchas-Cornejo, M.A., Villarreal-Colemnares, H., Calderon-Perez, J.A., Naranjo-Paramo., J., 1998. Evaluation of three feeding strategies on the culture of white shrimp *Penaeus vannamei* Boone 1931 in low water exchange ponds. Aquaculture Engineering 17, 21-28.

Mohanty, R.K., 2001. Feeding management and waste production in semi-intensive farming of *penaeus monodon* (fab.) at different stocking densities. Aquaculture International 9, 345-355.

Moorthy, M.S., Altaff, K., 2002. Role of natural productivity in modified extensive shrimp pond growing *Penaeus monodon* (penaeidae, crustacea). Indian Journal of Marine Sciences 31, 195-200.

Morales, A.E., Cardenete, G., de la Higuera, M., Sanz, A., 1994. Effects of dietary protein source on growth, feed conversion and energy utilization in rainbow trout, *Oncorhynchus mykiss*. Aquaculture 124, 117-126.

Moriarty, D.J., 1997. The role of microorganisms in aquaculture ponds. Aquaculture 151, 333-349.

Moss, S.M., Pruder, G.D., 1995. Characterization of organic particle associated with rapid growth in juvenile white shrimp, *Penaeus vannamei* Boone, reared under intensive culture conditions. Journal of Experimental Marine Biology and Ecology 187, 175-191.

Nunes, A.J.P., Gesteira, T.C.V., Goddard, S., 1997. Food ingestion and assimilation by the Southern brown shrimp *Penaeus subtilis* under semi-intensive culture in NE Brazil. Aquaculture 149, 121-136.

Nunes, A.J.P., Parsons, G.J., 2000. Size-related feeding and gastric evacuation measurements for the Southern brown shrimp *Penaeus subtilis*. Aquaculture 187, 133-151.

Nunes, A.J.P., Sá, M.V.C., Carvalho, E.A., Neto, H.S., 2006. Growth performance of white shrimp *Litopenaeus vannamei* reared under time and rate-restriction feeding regimes in a controlled culture system. Aquaculture 253, 646-652.

Parker, P.L., Anderson, R. K., Lawrence, A., 1989. A $\delta^{13}C$ and $\delta^{15}N$ tracer study of nutrition in Aquaculture: Penaeusvannamei in a pond grow-out system. In: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), Stable Isotopes in Ecological Research. Springer-Verlag, New York, pp. 288-303.

Patanaik, S., Samocha, T.M., 2009. Improved feed management strategy for *Litopenaeus vannamei* in limited exchange culture systems. World Aquaculture 40, 57-59.

Piadad-Pascual, F., 1993. Aquafeeds and feeding strategies in the Philippines.Pages 317-343 in: New, M.B., Tacon, A.G.J., Csavas, I. (Eds.), Farm-made aquafeeds. Proceeding of the FAO/AADCP, Bangkok, Thailand.

Piedad-Pascual, F., Cruz, E.M., Sumalangcay, A., 1990. Supplemental feeding of Penaeus monodon juveniles with diets containing various levels of defatted soybean meal. Aquaculture 89, 183-191.

Ponce-Palafox, J., Martinez-Palcacios, A., 1997. The effects of salinity and temperature on the growth and survival rates of juveniles white shrimp, *Penaeus vannamei*, Boone, 1931. Aquaculture 157, 107-115.

Prein, M., 2007. Comparative analysis of material flows in low input carp and poultry farming: an overview of concepts and methodology. In: Bartley, D.M., Brugere, C., Soto, D., Gerber, P., Harvey, B. (Eds.), Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO Fisheries Proceedings. No. 10. Rome. pp. 183-199.

Rana, K.J., Siriwardena, S., Hasan, M.R., 2009. Impact of rising feed ingredient prices on aquafeedsand aquaculture production. FAO. Fisheries and Aquaculture Technical Paper. No. 541. Rome, FAO. 2009. 63p.

Reymond, H., Lagardtre, J.P., 1990. Feeding rhythms and food of *Penaeus japonicus* Bate (Crustacea, Penaeidae) in salt water ponds: role of halophilic entomofauna. Aquaculture, 81, 125-143.

Roqued'Orbcastel, E., Blancheton, J.B., Aubin, J., 2009. Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. Aquaculture Engineering 40, 113-119.

Roy, A. L., Bordinhon, A., Sookying, D., Davis, D.A., Brown, T.W., Whitis, G. N., 2009. Demonstration of alternative feeds for the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters of west Alabama. Aquaculture Research 40, 490-503.

Roy, L.A., Davis, D.A., Whitis, G.N., 2012. Effect of feeding rate and pond primary productivity on growth of *Litopenaeus vannam*ei reared in inland saline waters of West Alabama, North American Journal of Aquaculture 74, 20-26.

Sedgwick, R.W., 1979. Effect of ration size and feeding frequency on the growth and food conversion of juvenile *Penaeus merguiensis*. Aquaculture 16, 279-298.

Seymour, E.A., Bergheim, A., 1991. Towards a reduction of pollution from intensive aquaculture with reference to the farming of salmonids in Norway. Aquaculture Engineering 10, 73-88.

Shipton, T.A., Hasan, M.R., 2013. An overview of the current status of feed management practices. In: Hasan., M.R., New, M.B. (Eds.), On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. pp. 3-20.

Smith, D.M., Dall, W., Moore, L.E., 1992. The natural food of some Australian penacids. In: Allan, G.L., Dall, W. (Eds.), Proceeding. Aquaculture Nutrition Workshop, 15-19 April 1991, Salamander Bay, Australia. NSW Fisheries Brackish Water Fish Culture Research Station, Salamander Bay, Australia, pp. 95-96.

Soares, R., Peixoto, S., Wasielesky, W., D'Incao., F., 2005. Feeding rhythms and diet of *Farfantepenaeus paulensis* under pen culture in Patos Lagoon estuary. Brazil Journal of Experimental Marine Biology and Ecology 322, 167-176.

Sookying, D., de Silva, S.F.D., Davis, D.A., Hanson, T.R., 2011. Effects of stocking density on the performance of Pacific white shrimp *Litopenaeus vannamei* cultured under pond and outdoor tank conditions using a high soybean meal diet. Aquaculture 319, 232-239.

Sookying, D., Davis, D.A., 2011. Use of soy protein concentrate in practical diets for Pacific white shrimp (*Litopenaeus vannamei*) reared under field conditions. Aquaculture 319, 141-149.

Tacon, A.G.J., 2000. Production of feeds for aquatic organisms in tropics with particular reference to Latin America and Caribbean. In: Cyrino, J.I., Moura, J.C., Caseiro, A.C., Sampaio, A.M.B. (Eds.), Proceedings - VIII Simpósio Brasiliero de Aqüicultura, Fundaçao de Estudos Agrários Luiz de Queiroz, Piracicaba, SP, Brasil. pp. 17-31.

Tacon, A.G.J., 2002. Thematic Review of Feeds and Feed Management Practices in Shrimp Aquaculture. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 69 pages.

Tacon, A.G.J., Hasan, M.R., Allan, G., El-Sayed, A.F.M., Jackson, A., Kaushik, S.J., Suresh, W.K.Ng,V., Viana, M.T., 2012. Aquaculture feeds: addressing the long-term sustainability of the sector in: Subasinghe, R.P., Arthur, J.R., Bartley, D.M., De Silva, S.S., Halwart, M., Hishamunda, N., Mohan, C.V., Sorgeloos, P. (Eds.), Farming the water for people and food. Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22-25 September 2010. Pp. 193-231. FAO, Rome and NACA, Bangkok.

Tacon, A.G.J., Hasan, M.R., Metian, M., 2011. Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. FAO Fisheries and Aquaculture Technical Paper No. 564, p. 87.

Talbot, C., Corneillie, S., Korsøen, O., 1999. Pattern of feed intake in four species of fish under commercial farming conditions: implications for feeding management. Aquaculture Research 30, 509-518.

Tan, R.K.H., Dominy, W.G., 1997. Commercial pelleting of crustacean feeds. Pages 520-549 in D'Abramo, L.R., Conklin, D.E., Akiyama, D.M. (Eds.), Crustacean Nutrition. World Aquaculture Society, Advances in World Aquaculture 6, Baton Rouge, Louisiana.

Thakur, D.P., Lin, C.K., 2003. Water quality and nutrient budget in closed shrimp (*Penaeus monodon*) culture systems. Aquaculture Engineering 27, 159-176.

Tidwell, J.H., Webster, C.D., Yancey, D.H., D'Abramo, L.R., 1993. Partial and total replacement of fish meal with soybean meal and distillers' by-products in diets for pond culture of the freshwater prawn (*Macrobrachium rosenbergii*). Aquaculture 118, 119-130.

Tiews, K., Bravo, S.A., Ronquillo, I.A., 1976. On the food and feeding habits of some Philippine shrimps in Manila Bay and San Miguel Bay. Philip. J. Fisher. 14, 204-213.

Trino, A., Sarroza, J., 1995. Effect of a diet lacking in vitamin and mineral supplements on growth and survival of *Penaeus monodon* juveniles in a modified extensive culture system. Aquaculture 136, 323-330.

Trino, A.T., Pen, V.D., Bolivar, E.C., 1992. Growth and survival of *Penaeus monodon* juveniles fed a diet lacking vitamin supplements in a modified extensive culture system. Aquaculture 101, 25-32.

Velasco, M., Lawrence, A.L., Castille, F.L., Obaldo, L.G., 2000. Determining optimal dietary protein level for *Litopenaeus vannamei* postlarvae. The Global Aquaculture Advocate 3, 46-47.

Venero, J.A., 2006. Optimization of dietary nutrient inputs for Pacific White shrimp *Litopenaeus vannamei*. Doctoral dissertation. Auburn University, Auburn, Alabama, USA.

Venero, J.A., Davis, D.A., Rouse, D.B., 2007. Variable feed allowance with constant protein input for the Pacific white shrimp *Litopenaeus vannamei* reared under semi-intensive conditions in tanks and ponds. Aquaculture 269, 490-503.

White, P., 2013. Environmental consequences of poor feed quality and feed management. In: Hasan, M.R., New, M.B. (Eds.), On-farm feeding and feed management in aquaculture, FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Williams, A.S., Davis, D.A., Arnold, C.R., 1996. Density-dependent growth and survival of *Penaeus setiferus* and *Penaeus vannamei* in a semi-closed recirculating system. Journal of the World Aquaculture Society 27, 107-112.

Williams, S., 1984. Official methods of analysis of the Association of Official Analytical Chemists.

Wyban, J.A., Lee, C.S., Sato, V.T., Seeney, J.N., Richards, W.K., 1987. Effects of stocking density on shrimp growth rates in manure-fertilized ponds. Aquaculture 61, 23-32.

Wyban, J.A., Sweeney, J.N., 1991. Intensive shrimp production technology. The Oceanic Institute, Honolulu, Haiwaii, USA.

Wyban, J., Walsh, W.A., Godin, D.M., 1995. Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp *(Penaeus vannamei*). Aquaculture 138, 267-279.

Zeigler, T.R., 2014. Why do we feed shrimp the way we do? Global Aquaculture Advocate 5, 28-30.

Zelaya, O., 2005. An evaluation of nursery techniques and feed management during culture of marine shrimp *Litopenaeus vannamei*. Doctoral dissertation. Auburn University, Auburn, Alabama, USA.