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A BIOECONOMIC MODEL OF RECIRCULATING SHRIMP PRODUCTION SYSTEMS

By

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A BIOECONOMIC MODEL OF RECIRCULATING SHRIMP PRODUCTION SYSTEMS

By

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To prevent disease outbreaks and increase competitiveness of U.S. shrimp products, U.S. aquaculture researchers have developed super-intensive, bio-secure, recirculating shrimp production systems since the early 1990s. The general objective of this research is to determine an optimal production strategy to maximize the net revenue for the system.

An inventory optimization model was built to determine the optimal harvesting week, shrimp size, and number of crops per year for experimental trials conducted at Gulf Coast Research Laboratory, Waddell Maricultural Center, and Oceanic Institute. Survival rate and price sensitivity analyses were conducted to see their impact on the system's net revenue. The optimal harvesting week solved by this model is determined by shrimp growth and feed functions. Price and survival rate can affect the value of net revenue, but do not impact the optimal harvesting week. Shrimp producers can use the developed inventory optimization model and results to manage their operations.

DEDICATION

I would like to dedicate this research to my husband Yu Yang, and my parents Jun Zhao and Baotian Zhou.

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I would like to express my sincere gratitude to all of the faculty and staff in the department of Agricultural Economics. First of all, a special thank goes to my major advisor, Dr. Terrill R. Hanson. Without his encouragement and guidance, I would never have been able to complete this thesis. The patience, devotion and efforts he showed while working with me inspired me to do my absolute best. Next, I am especially grateful to my committee members Dr. Stan R. Spurlock and Dr. M. Darren Hudson for their invaluable aid and direction to me. Also, I would like to thank Dr. Stan R. Spurlock again, as a graduate coordinator, who provided me a research assistantship offer two years ago so that I could come all the way to U.S. to enjoy a hopeful, interesting and dedicated study life. Finally, I would like to thank Dr. John T. Ogle and Mr. Jeff Lotz from Gulf Coast Research Laboratory (Ocean Springs, MS), Dr. Heidi Atwood, Dr. Craig Browdy, and Dr. Tong Ostrowski from Waddell Mariculture Center (Bluffton, SC), and Dr. Shaun M. Moss and Mr. Clete Otoshi from the Oceanic Institute (Oahu, Hawaii). I sincerely appreciate their selfless help on the data they provided for this thesis.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The U.S. has been the largest shrimp market and importer since 1998 and shrimp has become the most popular seafood consumed by U.S. consumers (Lem, 2006). Imports topped 500,000 tons, 518,000 tons, and 529,000 tons, respectively, in 2003, 2004, and 2005 (Lem, 2006). Shrimp consumption in the U.S. increased from approximately 200,000 tons in 1976 to 500,000 tons in 2002, a big margin higher in contrast to the smaller increase in the European Union, which increased from approximately 80,000 tons to 300,000 tons (Tveteraas, 2005). Per capita consumption of shrimp in the U.S. increased steadily from 1.5 pounds in 1982 to 3.7 pounds in 2002 (NOAA, 2003). The U.S. shrimp market is supplied by both domestic sources and foreign countries such as Thailand, China, Vietnam, and India (Lem, 2006).

During the 1990's, world shrimp mariculture was severely affected by viral diseases such as baculovirus, white spot syndrome virus, Taura syndrome virus, monodon baculovirus, and baculoviral mid-gut gland necrosis (Encyclopedia Aquaculture, 2000). U.S. shrimp production was not immune and Texas farm-raised marine shrimp production declined from 3.69 millions pounds in 1994 to 1.40, 2.00, and 2.56 million pounds in 1995, 1996, and 1997, respectively (Encyclopedia Aquaculture, 2000).

The price of shrimp in the U.S. has declined since 2003 due to increased supplies of wild harvested and imported maricultured shrimp from China, India, Malaysia, Indonesia, and Japan (Lem, 2006). Therefore, U.S. shrimp producers must lower production costs relative to rivals or grow larger shrimp or target niche markets desiring special traits, such as freshness and organic or natural products to remain competitive.

To prevent disease outbreaks and increase competitiveness of U.S. shrimp products, U.S. aquaculture researchers increased their research efforts to develop an intensive, bio-secure, and recirculating shrimp production system in the early 1990s. Technologically advanced intensive shrimp culture systems were developed in the late 1990s in the U.S. (Encyclopedia Aquaculture, 2000). At this point in time, these production systems were primarily for research but could approach commercial reality as system production levels increase and production and fixed costs are lowered.

These systems isolate shrimp production to an environment free of shrimp diseases. Bio-secure shrimp production systems are designed to avoid disease transmission pathways and are usually enclosed, covered, and re-circulate seawater. In addition, such systems can be located inland, away from coastal sites that may have become infected with shrimp viruses and can be located nearer to outlet markets (Posadas and Hanson, 2006). Therefore, this intensive production system can be an alternative strategy to traditional coastal and earthen pond culture systems in terms of disease prevention and lower cost compared to that of disinfecting huge volumes of water in the pond shrimp systems (Moss and Leung, 2006).

The main feature of the super-intensive shrimp production system is the extremely high stocking rate (i.e., number of shrimp initially stocked per cubic meter). In mariculture pond systems, the growth rate of shrimp is three to four grams per week, but in the super-intensive system, the growth rate of shrimp is only 1.5 grams per week.

However, this slower growth rate is made up for by the large difference in stocking rate. There may be twenty-five shrimp per cubic meter in ponds, compared to 150 to 700 shrimp per cubic meter in the super-intensive system (Moss and Leung, 2006).

Also, there are two separate production phases in the super-intensive system. The first phase begins with 0.10 gram shrimp that are grown to one gram post-larvae (PL), and this is called the nursery phase. The second phase grows the PL from one gram to harvest size at around twenty grams and is referred to as the grow-out phase. The person designing a super-intensive production facility must choose one or both of these phases.

The super-intensive recirculating shrimp production system requires a high technology level, which can result in a high production level. The natural environment is not relied upon at all except for some degree of temperature control, which can be kept below the lethal temperature level by using fans to cool down during the summer and above the lethal temperature level by using heaters to keep the system's water warm in the winter. All production inputs must be provided in this system. Inputs consist of high protein feeds, sterilized salt water, electricity, and aeration. Each input must be closely monitored and suitable backup systems are critical, as the breakdown of any single component will likely lead to the loss of all shrimp in a raceway.

The U.S. Marine Shrimp Farming Program (USMSFP) has done much of the biological, genetic, and engineering research for this system. This consortium is composed of members from the Oceanic Institute, Texas A&M University, University of Southern Mississippi, Waddell Mariculture Center, University of Arizona, Tufts University, and Nicholls State University (http://www.usmsfp.org/index.html).

Research at these institutes has shown that the super-intensive recirculating shrimp production system is biologically and technically feasible.

General Problem

The goals of the USMSFP consortium have changed from being primarily biotechnology research oriented to goals of commercialization of the systems. With this change in direction came the need to develop economic models that could maximize net revenue of these production systems, as research data have amassed from running their experimental production systems by the USMSFP consortium. Thus, whether the super-intensive recirculating production system is economically feasible compared to alternative shrimp sources has become the crucial test for these systems.

Specific Problems

In 2000, the USMSFP contracted with the Department of Agricultural Economics at Mississippi State University (MSU) to develop a cost and return model for the super-intensive shrimp production systems to evaluate the economic feasibility of the system. Dr. Terry Hanson and Dr. Benedict Posadas from MSU developed a bioeconomic model (Hanson-Posadas model) for the super-intensive recirculating shrimp production system (Posadas and Hanson, 2006). This model simulates construction costs, equipment purchases, and operational expenses for the production and harvesting of shrimp in the super-intensive system. Result outputs include economic analyses (NPV, IRR, payback period), sensitivity analyses, annual cash flows, and enterprise budgeting (cost of production and annual net returns).

Transforming the Hanson-Posadas into an optimization model is a beneficial progression of the model as the model will now be able to answer questions concerning optimal harvesting strategies and maximization of net revenue for the system. The first step in the model transformation to evaluate the economic feasibility is to determine the optimal harvesting strategy to maximize the net revenue of the system, followed by the second step of inserting the optimal strategy into the Hanson-Posadas model which then conducts an economic feasibility analysis. Furthermore, the model needs to determine how shrimp price and growth parameters affect the optimal strategy and the net revenue of the system.

Currently, shrimp growth parameters for these intensive systems beyond the 24g size are not well known. Thus, if the final desired shrimp size is above 25g, the growth rate of these sizes in the high stocking environment of the intensive system can only be based on educated guesses. It might be assumed that a higher price for a larger shrimp size will be beneficial to annual net returns, but production cycle duration and number of crops per year will heavily influence this assumption.

Price received by the producer is an important parameter in any model that optimizes economic returns. Figure 1.1 shows that shrimp is priced by size categories. The price for larger shrimp is higher than that for smaller shrimp: for example, 15-20 count shrimp (15-20 shrimp per pound) may sell for $8.99/lb, versus $3.99/lb for 24-30 count shrimp. Sales revenue will increase if shrimp are allowed to grow to larger sizes due to higher prices, but additional production costs and fewer crops per year may reduce the annual net return below that for smaller sized shrimp.

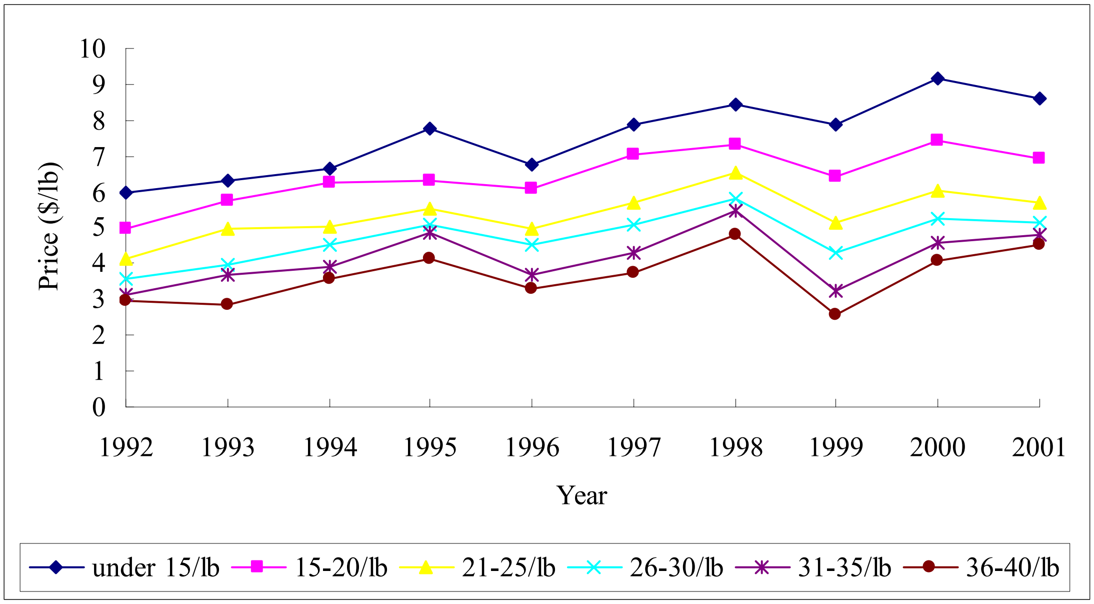

Figure 1.1 Ex-Vessel Price of Shrimp Landed in January in the Northern Gulf of Mexico (National Marine Fisheries Service).

The price difference among shrimp size categories is a crucial element in the determination of whether to grow larger or smaller sized shrimp. The size of shrimp grown will determine the number of completed shrimp production batches that can be completed in a year. Larger sized shrimp need longer time periods and result in fewer completed batches per year. Smaller sized shrimp need shorter production periods and result in more completed batches per year. However, larger sized shrimp sell for higher prices than smaller sized shrimp. Thus, price margins between size categories become a key issue on the optimal production strategy and economic viability of the intensive shrimp production systems.

Objectives

The general objective of this research was to determine an optimal harvesting strategy to maximize annual net revenue from the super-intensive recirculating shrimp production system. The optimal solution was dependent upon the shrimp stocking rate, survival rate (ratio of the number of surviving shrimp divided by the number of shrimp initially stocked), price received for each shrimp size category, and associated costs of production such as feed cost and Post Larvae (shrimp initially stocked) Cost.

This general objective was accomplished through the following specific objectives:

1) Determine the optimal harvesting week, the optimal shrimp size to be harvested, and the optimal number of crops per year to maximize the annual net revenue of the super-intensive production system;
2) Determine the impacts of shrimp survival rate on the optimal solution and the maximized net revenue of the production system; and
3) Determine the impacts of historic shrimp prices by size categories from 2002 to 2006 on the optimal solution and the maximized net revenue of the production system.

Data to accomplish these objectives came from experimental production studies completed by the USMSFP research centers.

Potential Users of Results

Shrimp researchers will be able to use the bioeconomic optimization model to guide their research activities toward areas providing greater dollar returns or for lowering cost of production in the super-intensive recirculating shrimp systems. Shrimp producers will be able to use the model in managing their operations to maximize annual net returns. Specifically, producers will be able to optimize their harvesting choices to maximize net revenues of their systems. Investors and bankers who are interested in financing commercial super-intensive shrimp operations will be able to better evaluate capital investments, production costs, and profit potential based on the model results and decide whether such projects are economically feasible to finance.

CHAPTER II

LITERATURE REVIEW

This literature review consists of three sections. The first section focuses on studies of the super-intensive recirculating shrimp production system from a biological perspective; the second section focuses on studies of the system from an economic perspective; and the third section focuses on studies of bioeconomic modeling of the system. The second and the third sections are reviewed and analyzed as they are relevant to this thesis, while the first section describes the biological background on the production system.

Biological Perspective

The literature review from the biological perspective has been divided into the following: the technical feasibility of the super-intensive recirculating shrimp production system and insights into shrimp growth and feeding in these systems.

Technical Feasibility

Moss and Leung (2006) found that “recirculating aquaculture systems (RAS)” can be an alternative to the traditional pond system in the production of shrimp. The recirculating system has advantages such as protecting shrimp from being infected by viruses and being located inland and near market outlets, which was explained in Chapter One.

Bratvold, Lu, and Browdy (1999) studied a comparison analysis on “disinfection and microbial community establishment” and shrimp production between a bio-secure, enclosed pond with initially disinfected water in it and three control ponds which were not enclosed and with water which was not disinfected. Results of their analysis indicated the “technical feasibility” of shrimp growth in the bio-secure, enclosed pond with initially disinfected water.

Lightner (2005) defined bio-security for shrimp aquaculture as the action of keeping out harmful pathogens or viruses from cultured aquatic stocks in brood stock facilities, hatcheries, and farms, or from entire regions or countries to avoid diseases. The application of bio-security to shrimp aquaculture will contribute significantly to making the shrimp mariculture industry much more sustainable and environmentally responsible well into the future, although not being accomplished easily in the short term. The super-intensive recirculating shrimp production system must adhere to the strict application of bio-security measure or else the slightest disease outbreak will quickly spread to all shrimp with disastrous results.

Shrimp Growth and Feeding

Moss, Otoshi, and Leung (2005) found that compensatory growth occurs in *Litopenaeus vannamei* as partial harvesting leads to a lower stocking rate during the production cycle compared to the single harvesting in the super-intensive recirculating system when the initial stocking rates of both partial and single harvesting regimes are the same. Compensatory growth occurs when “growth restriction” is alleviated and growth rate increases to compensate for “lost” or restricted growth.

Research on the shrimp nursery phase duration (Yta, Rouse, and Davis, 2004) and high stocking rate (Moss and Moss, 2004) at this stage was conducted to determine survival and growth rates of *Litopenaeus vannamei*. Their studies found the nursery stage had a positive impact on production primarily in terms of size uniformity. Also, it was found that use of artificial substrates in raceways could be used to mitigate the potential negative effects of high stocking rates on growth of *Litopenaeus vannamei* in nursery systems. Therefore, shrimp producers may be able to take advantage of the benefits derived from the nursery phase of production to improve farm profitability by increasing stocking rates without compromising shrimp growth.

Ucozler (2006) stated that "shrimp are omnivorous creatures." Different species of shrimp have different food priorities. Some shrimp would prefer to eat the food directly provided for them, and others would prefer to eat microorganisms. The micro-organism can be reproduced by the feeding in the tank. Tacon, Nates, and McNeil (2006) pointed out that microorganism played an important role in the nutrition and health of shrimp cultured "under green-water-or zero-water-exchange" conditions. They also stated that shrimp would continuously eat if food were offered frequently and in a small quantity each time. Thus, all these factors may affect shrimp feed functions.

Economic Perspective

The literature review from the economic perspective has been divided into the following:

1. Studies focusing on the economic feasibility of the super-intensive recirculating shrimp production system;

2. Studies focusing on the impacts of harvesting choices, stocking rate, and compensatory growth after partial harvesting on the maximization of the net revenue of the system;
3. Studies focusing on the impact of shrimp pricing by size category on the profit maximization of the super-intensive recirculating shrimp production system; and
4. Studies focusing on shrimp production functions.

Economic Feasibility

As stated previously, Moss and Leung (2006) found that a “recirculating aquaculture system (RAS)” can be an alternative to the traditional pond system to produce shrimp. A comparison of economic analysis between these two systems indicates that the total production cost per kilogram of output from the recirculating system is lower than that from the pond system. The reason is that the stocking rate and number of crops in the recirculating system can be much higher than those in the pond system, which results in economies of size. Results of the economic sensitivity analyses on production factors such as survival rate, growth rate, and feed conversion ratio also indicate that the “recirculating aquaculture system (RAS)” can be a viable alternative to the pond system. Also, Posadas and Hanson (2006) pointed out that it can be economically viable to add the nursery phase to the recirculating system if PL can be nursed to the targeted size and mortality rate is relatively low at the end of this nursery phase. In an earlier study, Moss and Leung (1999) found that a “biosecure growout system” can be profitable if the stocking rate is above 200 shrimp per m^3 and other production parameters can be relatively high, such as survival rate and growth rate. However, they did not attempt to optimize harvesting strategies to maximize net revenues of the recirculating systems.

Wyk (2001) analyzed two strategies using enterprise budgeting and found recirculating production systems to be profitable. These two strategies are as follows: 1) multiple batches per year are produced so that production can be increased with fixed cost and capital requirement the same as those of single batch per year; and 2) the size of the individual system is enlarged and the number of the systems is decreased so that labor costs can be reduced and economies of scale obtained. However, optimization strategies to maximize the net revenue of the system still needed to be researched.

Harvesting Choices, Stocking Rate, and Compensatory Growth

The single harvesting approach (Hanson, 2006) has only one harvest when shrimp reach the targeted size. The partial harvesting approach (Hanson, 2006) grows the shrimp population biomass to the biological limit of the production system, harvesting some portion of the shrimp population (biomass) in the system, and then continue growing the un-harvested shrimp until the final harvest size and carrying capacity of the system is reached.

There are two cases concerning the initial stocking rate for these two harvesting approaches. The first case occurs when the initial stocking rates of the partial and single harvesting approaches are the same. In this case, partial harvesting can be more profitable than single harvesting due to compensatory growth if the additional cost for partial harvesting is less than the opportunity cost for single harvesting in the super-intensive recirculating system (Moss, Otoshi, and Leung, 2005). However, the harvesting strategy has not been optimized. The second case occurs when the initial stocking rate of the partial harvesting approach is higher than that of the single harvesting approach. For "efficiency" of the super-intensive recirculating system, the partial harvesting approach can relax the "maximum biomass" constraint, but the single harvesting approach can not. Based on simulation data from a bioeconomic model and price data by size categories from NMFS, Hanson, Lawrence, and Posadas (2006) found that partial harvesting can be more profitable than single harvesting if the initial stocking rate, harvest size, and percentage level of partial harvesting are optimal. Also, they pointed out that maximizing or increasing biomass by partial harvesting does not necessarily maximize the profit of the system because final profitability is a function of the shrimp price for each size category and different price margins between shrimp size categories. Other pertinent factors involved in maximizing the profit of the system are as follows: survival rate, stocking rate, growth rate, partial harvesting percentage, targeted shrimp size, and number of crops per year. However, no specific optimal mix of these factors has been obtained. In addition, their economic analysis was based on growth and other biological parameters that came from USMSFP consortium members. Research was used in the simulation of the bioeconomic model. To evaluate the economic feasibility of the super-intensive production systems, growth and feed data should come directly from consortium members' experiments of the systems.

Shrimp Pricing by Size Category

Few studies have been conducted on the impact of shrimp pricing by size category on the maximization of net revenue of any shrimp production system. Bjorndal (1988) made an assumption that output price is a linear function of weight for his bioeconomic model of fish. Based on this approach, Mistiaen and Strand (1999) found that “piecewise-continuous” price functions cause “stepwise-nonlinear” response as different parameters change. This assumption implied that pricing should be continuous. However, in the real world shrimp market, price margins occur between size categories so that price is a discontinuous function depending on the size instead of a continuous linear price function.

Hanson, Lawrence, and Posadas (2006) pointed out that shrimp prices by size categories and price margins have impacts on the percentage level of partial harvesting that should occur, harvesting time, and the net return of the system. Also, Posadas and Hanson (2006) pointed out that a database of monthly shrimp selling prices by size categories (to be calculated into revenue) were added into the bioeconomic model; as mentioned in the Specific Problem section of Chapter One. Bjorndal, Lane, and Weintraub (2004) concluded that shrimp selling price is an important factor to optimal input and harvesting choices since the individual size and quality determine the price, which itself fluctuates. However, they did not Figure out how to optimize the percentage level and harvesting time to maximize the net return of the system, based on the prices and price margins.

Liao and Liao (2006) did “a comparative analysis of costs and returns” of black tiger and white shrimp farming in Taiwan to show that the means to improve net returns are to increase price, decrease production costs, and to increase productivity. They did not point out that shrimp is priced by size categories. Also, they did not determine the optimal harvesting time and size of shrimp to be produced to maximize net returns.

Shrimp Production Function Models

The Cobb-Douglas function was used by Liao and Liao (2006) to perform regression analysis of black tiger shrimp production in Taiwan with respect to land, seed, feed, stocking rate, survival rate, labor, and capital. However, the model can not be used to determine the optimal harvesting time and size to maximize net revenue since it did not involve time as an independent variable in the production function. Additionally, profits after the harvest season were not calculated and compared. Yu, Leung, and Bienfang (2006) found that artificial neural networks (ANN) can surpass the traditional statistical regression techniques in predicting shrimp growth in a commercial situation. The reasons are as follows: 1) ANN can include more factors related to shrimp growth than the traditional techniques, such as water temperature, feed supply, stocking rate, and biomass; 2) shrimp growth predicted by ANN is more accurate than that predicted by the traditional techniques. However, since the dataset they used is from only one farm and covers just one year, their findings cannot be extended to all shrimp farms, especially when all factors related to shrimp growth are not known. Therefore, traditional regression techniques are still used to predict shrimp growth in this thesis.

Bioeconomic, Optimization, and Inventory Modeling

The bioeconomic model mentioned in Chapter One was developed to determine the profitability of the super-intensive recirculating shrimp production system under varying assumptions (Hanson and Posadas, 2004 and 2006). Their bioeconomic model is a spreadsheet simulation model: once parameters for all the factors of the system such as shrimp selling prices, inputs (PLs, electricity, salt, water, chemicals, labor, etc.) and biological parameters (stocking rate, growth rate, survival rate, harvesting size, and stocking size) are input into the model and run, simulated economic results can be obtained quickly. These results covered economic analyses, sensitivity analysis, annual cash flows, and enterprise budgeting. Output results estimate construction costs, equipment purchases, and operational expenses for producting and harvesting shrimp growth in the system. Therefore, the bioeconomic model can evaluate economic feasibility of the system under current biological and production levels and can project economic performance of the system under future predicted parameters. Also, this model was modified to assist entrepreneurs in their decision to invest by facilitating investment sensitivity analyses for the system through analysis of varying assumptions, simulation returns, and output of results before actual investment occurs. Hanson and Posadas (2005) pointed out two critical assumptions that were made when this bioeconomic model was used. The first assumption was that PL supply would be available over a long time period as would be required to produce back-to-back crops throughout the year; and the second assumption was that the management and technology would be capable of back-to-back production batches over a long time period. However, their model is not an optimization model; it can not optimize combinations of the above factors to maximize the net revenue of the system. Therefore, an inventory optimization model was built to solve the optimal harvest strategy to be integral part of the Hanson-Posadas bioeconomic model to evaluate the economic feasibility of the super-intensive recirculating production system.

Bjorndal (1988) specified a simple bioeconomic model with output price and input costs added to analyze optimal harvesting time to maximize the present value of net revenue and conducted sensitivity analyses regarding different parameters' influences on the optimal solution. However, this model cannot fit the problem of this thesis although it is an optimization model. The reason is as follows: 1) the growth function is not specified; 2) the price assumption is not realistic; 3) the optimal solution focused only on the harvest time, not covering the number of shrimp to be harvested; 4) the feed function is not specified; and 5) this model cannot show on-going production and inventory levels.

Linear programming (LP), as a management science technique for optimization, has been widely used in agricultural management to make optimal decisions to maximize net revenue. Hatch et al. (1987) used a LP analysis to show the optimal mix of farm activities among the growth stages of catfish, which indicated that fingerlings were preferred but also had the highest economic risk and greatest market limitations. Dunning (1989) developed a whole-farm LP model aimed at the selection of optimal stocking rates and grow-out cycle lengths for shrimp pond culture in Ecuador. Stanley (1993) built a similar model for shrimp farming in Honduras; however, her study was based on 1992 pond systems (prior to the onset of any major viral diseases in the country), and some critical model specifications (such as assuming a constant year-round survival rate of 70%) do not reflect current shrimp farming conditions. Linear programming cannot be used in the methodology of this thesis because nonlinear relationships exist such as shrimp price being a discontinuous function of shrimp weight.

Engle and Pounds (1993) developed a multi-period, risk programming model that was designed to select optimal production management strategies for catfish production. When cash flow and off-flavor considerations were added to the model, the optimal result changed from its original solution of single batch strategies stocked with 18-20 centimeter fingerlings at 14,800 per hectare to multiple batch strategies with high stocking rates of larger fingerlings. This model's results partially explain why catfish farmers often utilize multiple batch production strategies even though potential net returns are highest from single batch production systems. Similarly, multiple crop production strategies with high stocking rates were utilized to attain the objectives in this thesis.

In summary, this literature review stated current and past research on the super-intensive recirculating shrimp production system from three aspects: the biological, the economic, and the modeling aspects. Moreover, the review provides a basis and background for this thesis.

CHAPTER III

CONCEPTUAL FRAMEWORK

This chapter is divided into three sections. The first section described the theory of net revenue maximization. The second section explains why it is better to maximize net revenue per unit of time instead of on a per production cycle. The third section states the theory of production functions. The last section introduces techniques used in the inventory optimization modeling of this thesis.

Maximization of Net Revenue

Net Revenue is defined as follows:

$$\prod \equiv R - C \tag{3-1}$$

where $\prod$ is net revenue, R is total revenue and C is total cost.

$$R = P * Q \tag{3-2}$$

where P is selling price of the output and Q is quantity of the output.

$$C = FC + VC \tag{3-3}$$

where FC is fixed cost and VC is variable cost. $\prod$, R and C are functions of Q respectively from the output perspective (Figures 3.1 and 3.2).

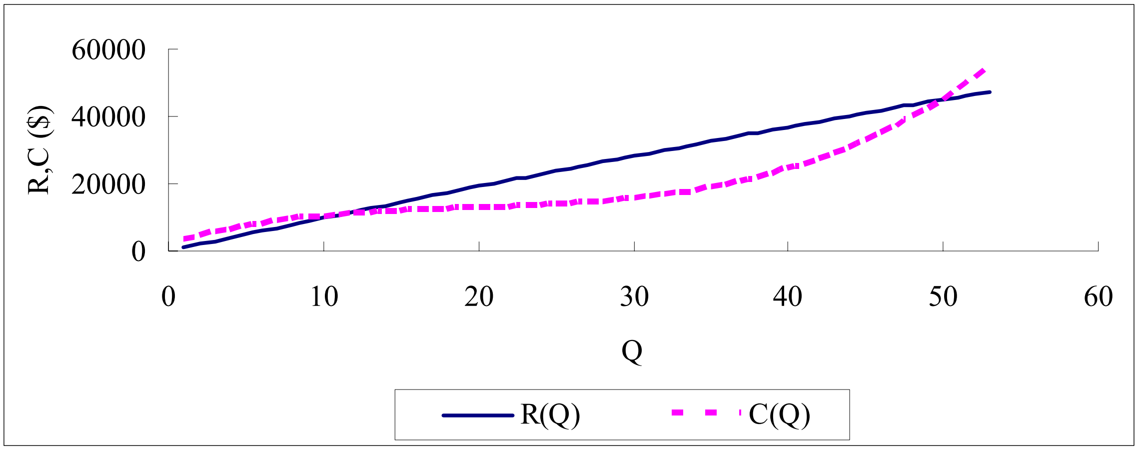

Figure 3.1 Total Revenue and Total Cost

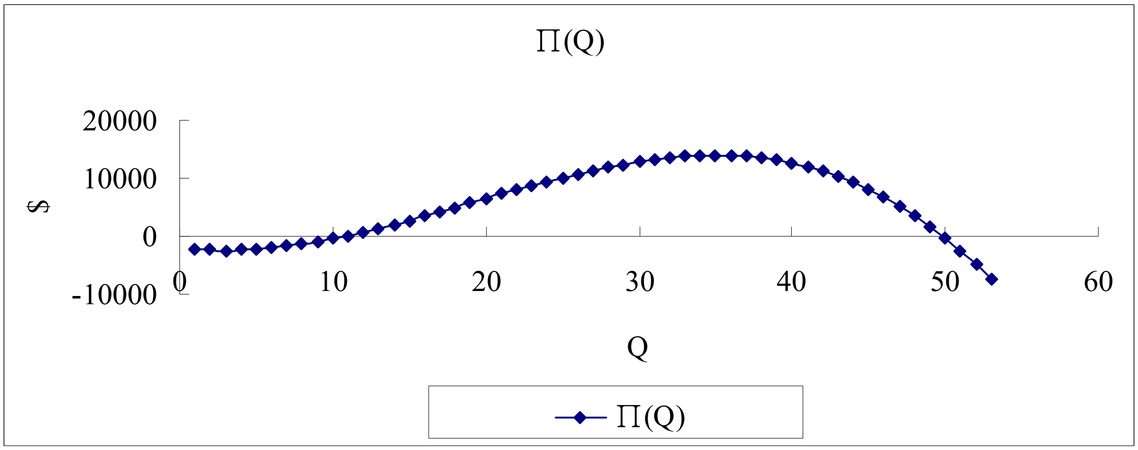

Figure 3.2 Net Revenue

There are two steps to maximize net revenue (Chiang, 2005). The first step is to take the first derivative with respect to Q of equation (3-1) as follows:

$$\prod(Q)' = R(Q)' - C(Q)' \quad (3\text{-}4)$$

Set the first derivative equal to zero as follows:

$$R(Q)' - C(Q)' = 0 \quad (3\text{-}5)$$

Or

$$MR = MC \tag{3-6}$$

where MR is marginal revenue and MC is marginal cost (Figure 3.3). Solve the choice variable Q to get a solution represented as Q*. The second step to maximize net revenue is to take the second derivative with respect to Q of equation (3-1) or to take the first derivative with respect to Q of equation (3-4) as follows:

$$\prod(Q)'' = R(Q)'' - C(Q)'' \tag{3-7}$$

Put the value of Q* into equation (3-7) to calculate. If $R(Q^*)'' - C(Q^*)''<0$, Q* is the optimal value of Q to maximize net revenue; if $R(Q^*)'' - C(Q^*)''\geq 0$, Q* is not the optimal value of Q to maximize net revenue.

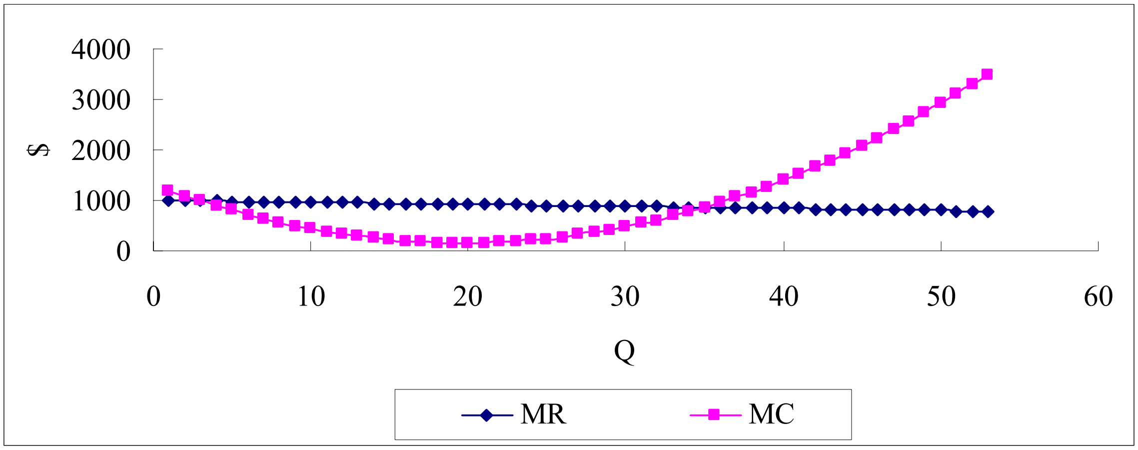

Figure 3.3 Marginal Revenue and Marginal Cost

Maximize Net Revenue per Unit of Time

When time is introduced into the economic analysis, the goal of maximizing net revenue needs to be revised from one production cycle to one unit of time since a manager wishes to maximize net revenue for each accounting period, however long the production cycle might be. An accounting period is usually for a year. Therefore, the net revenue per year is obtained from the net revenue per week multiplied by 52 weeks or the net revenue per day multiplied by 365 days. Therefore, net revenue per day or per week is maximized simultaneously with the maximization of net revenue per year.

An example of a dry-lot cattle feeding operation will be used to explain this point. This example is from Doll and Orazem's (1978) "Production Economics: Theory with Applications."

Estimated total time revenue and total time cost functions are stated as:

$$TTR = 120 + 0.6\,N^{2} - 0.02\,N^{3} \tag{3-8}$$

$$TTC = 120 + 2.0\,N + 0.0067\,N^{3} \tag{3-9}$$

where N is time in ten day feeding units.

The net revenue equation can be derived by subtracting equation *TTC* from equation *TTR*. This gives

$$NR = -\,0.0267\,N^{3} + 0.6\,N^{2} - 2\,N \tag{3-10}$$

An optimal solution of $N = \dfrac{1.2 + \sqrt{1.44 - 0.64}}{0.16} = 13.1$ units can be calculated by equating the marginal net revenue to zero. Therefore, 131 days of feeding will maximize the net revenue for an operation cycle (as N is in 10 day feeding increments).

An average net revenue equation can be obtained by dividing the net revenue equation by units of time, *N*. Thus, average net revenue is

$$\text{Average Net Revenue} = -\,0.0267\,N^{2} + 0.6\,N - 2 \tag{3-11}$$

An optimal unit of time, $N = 11.2$, can be calculated by setting the first derivative of the average net revenue equation equal to zero. Therefore, 112 days of feeding will maximize the average net revenue per unit of time.

Comparing the net revenues from both cases and assuming no discounting, the net revenue is \$ 16.74 at the end of 131 feeding days in the first case. It is calculated by substituting $N = 13.1$ into the net revenue equation. The number of production cycles for a year is 2.8, calculated by dividing 365 days by 131 days. Thus, the net revenue for a year is \$ 46.87, calculated by multiplying \$ 16.74 by 2.8 cycles. In the second case, the net revenue is \$ 15.35 at the end of 112 feeding days. It is calculated by substituting $N = 11.2$ into the net revenue equation. The number of cycles for a year is 3.3, calculated by dividing 365 days by 112 days. Thus, the net revenue for a year is \$ 50.66, calculated by multiplying \$ 15.35 by 3.3 cycles. Therefore, the total net revenue for a year by maximizing average net revenue per unit of time is more than that from maximizing the net revenue for a single operation cycle (Figures 3.4 and 3.5).

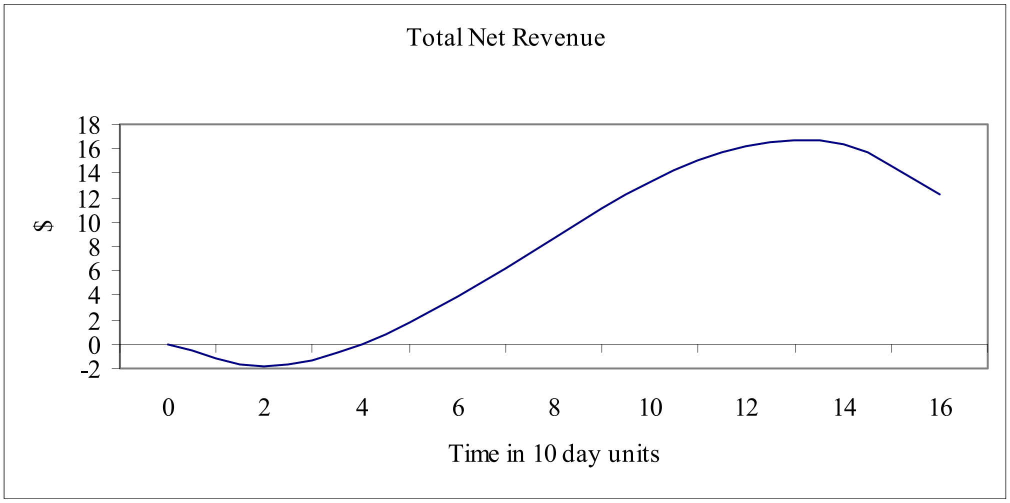

Figure 3.4 Total Net Revenue for a Cattle Feeding Operation

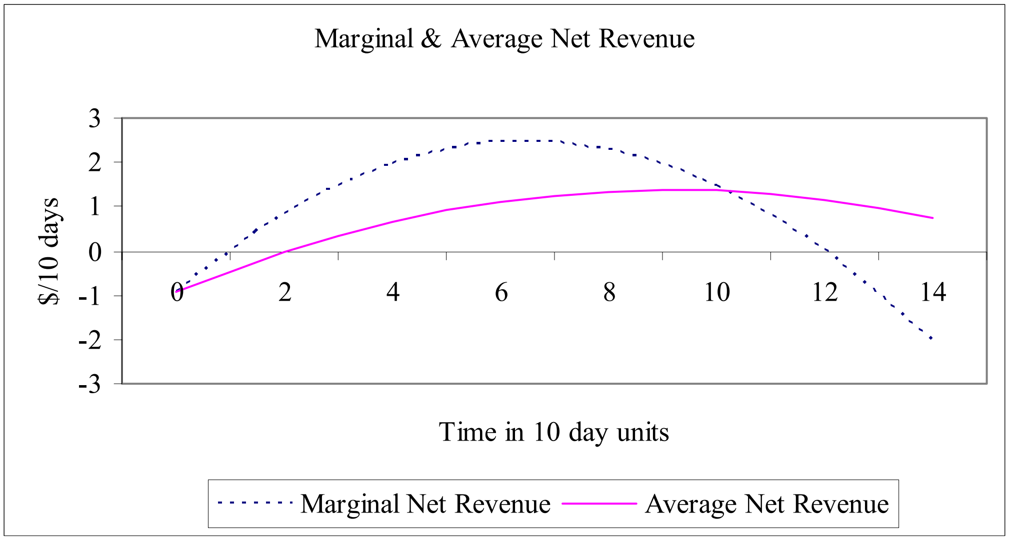

Figure 3.5 Marginal Net Revenue and Average Net Revenue for a Cattle Feeding Operation

Production Function

To define a growth function and a feed function of shrimp is the first primary step to accomplish the objective of this thesis. The determination of the two functions is based on the theory of production function, which was described as follows. Then the growth function and the feed function were determined.

TPP, APP, and MPP

TPP (total physical product) is a production function that describes the technical relationship that transforms inputs (resources) into outputs (commodities) (Beattie and Taylor, 1985). TPP is represented as follows:

$$Y = f(x) \tag{3-12}$$

where Y denotes quantity of the output, x denotes the quantity of each input and f is the functional form chosen to best fit the observed data points. APP (average physical product) is defined as follows:

$$APP \equiv Y/X \equiv f(x)/x \tag{3-13}$$

MPP (marginal physical productivity) is defined as follows:

$$MPP \equiv d(TPP)/dx \equiv dy/dx \equiv df(x)/dx \equiv f'(x) \tag{3-14}$$

TPP, APP and MPP are graphically depicted in Figures 3.6 and 3.7 for the one input, one output case.

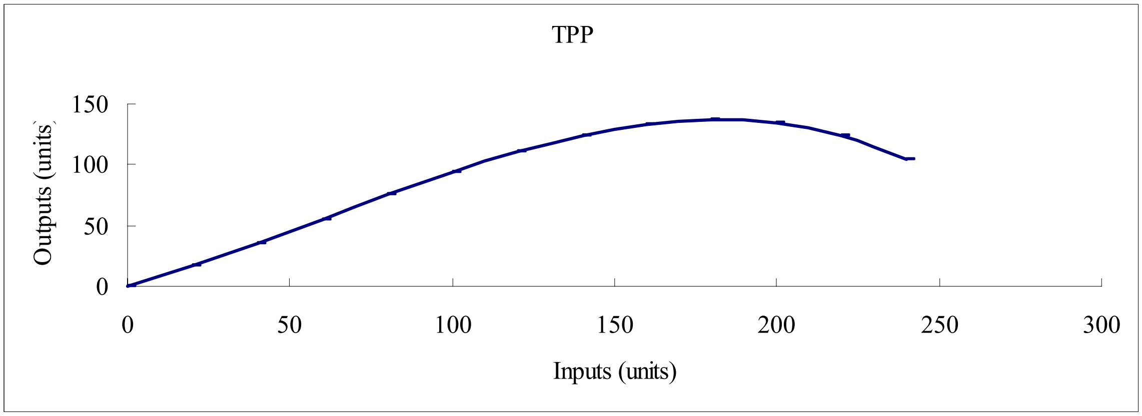

Figure 3.6 TPP

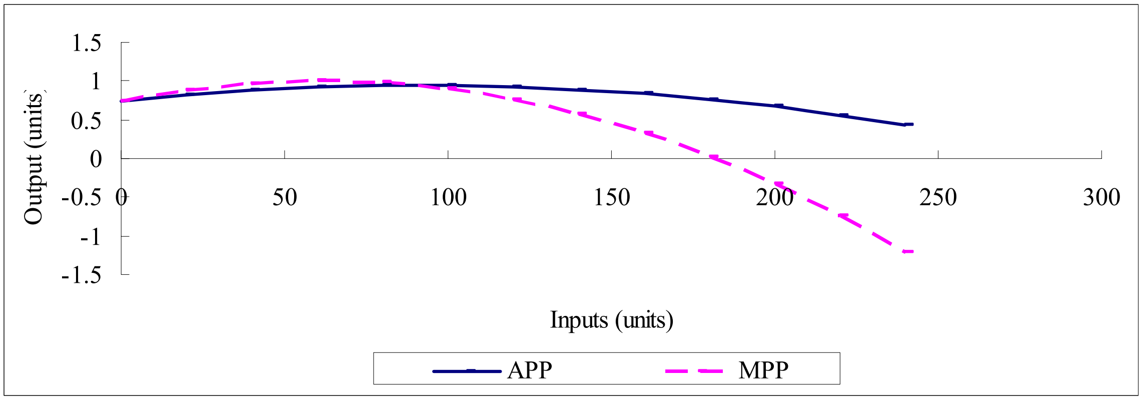

Figure 3.7 APP and MPP

Regression Model for Growth Function and Feed Function

Based on TPP theory, growth as the output can be a function of time as the input and feed can be a function of time. A quadratic function, based on empirical production studies of USMSFP researchers, was used to perform regression analysis for both growth and feed functions.

Inventory Model

An inventory model is used to plan production and update shrimp inventory levels for each time period. In an inventory model, the quantity of the commodity at the end of the current period should be equal to the quantity at the beginning of the next time period. The quantity of the commodity at the end of the current period is calculated as the quantity at the beginning of the period plus the quantity of the output produced during this period minus the quantity of the output sold or died during this period. The inventory model can be applied to plan the quantity of shrimp to be stocked in the production system, the quantity of shrimp to be harvested and the optimal harvesting time schedule.

To sum up, this conceptual framework covered the underlying theories for the maximization of net revenue and the production function. Also, the theories explained why the objective of this thesis should be to maximize net revenue per unit of time instead of maximizing net revenue of only one production cycle. Finally, this chapter introduced the inventory modeling technique. These interpretations provided foundations for the methodology and procedures of the next chapter.

CHAPTER IV

METHODS AND PROCEDURES

This chapter first explains the data sources and the manipulation of them and adjustments to the data. Next, it describes the procedures in feed and growth function estimates. Third, it explains the inventory model and assumptions and defines the variables in the model. Fourth, it describes how to get the optimal harvesting week to maximize net revenue per year by the inventory model; and finally it discusses shrimp price analysis.

Data

USMSFP consortium members conducting production research in super-intensive recirculating shrimp production systems have provided the base data for the biological functions developed in this research. Pacific white shrimp, *Litopenaeus vannamei* was reared in the systems. The initial stocking rate must be less than or equal to 705 PLs per m^3 as this is the greatest stocking rate yet used by the consortium. Also, the shrimp biomass must be less than or equal to 6,000 g per m^3 during any production week to meet the biological carrying capacity restrictions of consortium raceway production systems. Individual shrimp weight must be less than or equal to 35 g to meet market restrictions and unknown production parameters (not yet achieved by any consortium member). Three groups of data came from the Gulf Coast Research Lab (GCRL), the Waddell

Mariculture Center (WMC), and the Oceanic Institute (OI).

GCRL data came from shrimp culture experiments using the super-intensive recirculating shrimp production system located at the University of Southern Mississippi campus at Ocean Springs, MS. This data came from initial production trial experiments of the new facility. Twelve tanks were used to grow shrimp, and two batches were processed for each tank. The first batch ran from May 15 to September 13, 2006, and the second batch ran from September 14 to December 7, 2006. The stocking rate of each tank for the first batch was 401 shrimp per m^3, and the stocking rate of each tank for the second batch was 396 shrimp per m^3. For the first batch, each of tanks 1, 4, 7, 9, 10, and 12 had a volume of 40 m^3 of water, and each of tanks 2, 3, 5, 6, 8, and 11 had a volume of 80 m^3 of water. For the second batch, all twelve tanks had a volume of 40 m^3 of water. Also, for the second batch, tanks 3, 6, 8, and 10 were filled with 100% new bleached water and kept no "old" water from previous runs. However, tanks 1, 2, 5, and 11 were filled with 90% new bleached water and kept 10% "old" water from previous runs, while tanks 4, 7, 9, and 12 were filled with 10% new bleached water and kept 90% "old" water from previous runs. Due to death of shrimp in tanks 3, 4, 5, 6, 7, 8, and 10 of the first batch and the short growth period for the second batch, data from only two groups were used. The first group used was from tanks 1, 9, and 12 of the first batch (GCRL-1, 9, 12), and the second group used was from tanks 2 and 11 of the first batch (GCRL-2, 11). No second batch data were used.

Raw data from GCRL were provided on average individual shrimp weight at the end of each week and quantity of feed fed per day in each of the twelve tanks. Since the inventory model mentioned in Chapter Three was based on a weekly period and kept track of revenue and cost, the quantity of feed fed per day was converted to a weekly basis. Therefore, the quantity of daily feed fed was summed for seven days. Data of the quantity of feed fed per cubic meter of each tank on a weekly basis were calculated as the weekly quantity of feed fed divided by the volume of water in each tank.

WMC data came from shrimp culture experiments using the super-intensive recirculating shrimp production system located at the Waddell Mariculture Center in Bluffton, SC. Data from trial 8, 9, 10, 11, and 12 were provided on a weekly basis. Trial 8 ran from July 15 to November 12, 2003; trial 9 ran from July 15 to November 14, 2004; trial 10 ran from June 2 to September 22, 2005; trial 11 ran from November 15, 2005, to March 28, 2006, and trial 12 ran from August 1 to December 26, 2006. The stocking rate for trials 8, 9, 10, 11, and 12 was 420 shrimp per m^3, 450 shrimp per m^3, 499 shrimp per m^3, 371 shrimp per m^3, and 246 shrimp per m^3, respectively. Due to the short growth period for trial 10 and 12, data from only trial 8, 9, and 11 were used. Average individual shrimp weight at the end of each week for each trial was provided by averaging the individual weight of a sample of 25 shrimp randomly taken from that trial at the end of each week. The quantity of feed fed for each trial was provided on a weekly basis. Data for quantity of feed fed per cubic meter for each trial was calculated as the quantity of weekly feed divided by the volume of water for each trial.

OI data came from shrimp culture experiments using the super-intensive recirculating shrimp production system located at the Oceanic Institute (Oahu, HI). Two trials of data, called trial 14 and trial 23, were provided. Trial 14 had a stocking rate of 705 shrimp per m^3 and trial 23 had a stocking rate of 301 shrimp per m^3. In addition, trial 14 kept records for 12 weeks from February 22 to May 19, 2005, and trial 23 kept records for 14 weeks from January 16 to April 17, 2006. Average individual shrimp weight at the end of each week was provided for both trials. Also, the quantity of feed fed for each trial was provided on a weekly basis. Data for quantity of feed fed per m^3 for each trial was calculated as the quantity of weekly feed divided by the volume of water in each trial raceway.

Growth and Feed Regression

Both growth and feed regression functions were estimated to calculate weekly revenue and cost and then to maximize net revenue per year through the inventory model. Based on the regression model in Chapter Three, the growth regression function was estimated as:

$$W_i = \beta_0 + \beta_1 * X + \beta_2 * (X)^2 \tag{4-1}$$

where Wi is average individual shrimp weight at the end of each week i, and X is the week number of the production cycle. The Feed regression function was estimated as:

$$F_i = \beta_0 + \beta_1 * X + \beta_2 * (X)^2 \tag{4-2}$$

where F_i is the quantity of feed fed per m^3 per week.

Therefore, average individual shrimp weight at the end of each week was used as the dependent variable when estimating the growth regression function. Also, the quantity of feed fed per cubic meter per week was used as the dependent variable when estimating the feed regression function. Two independent variables used were the week number and week number squared. Both growth and feed regression functions were estimated using the Ordinary Least Squares (OLS) procedure.

Aggregated regression functions of growth and feed were estimated for each of the five sets of data provided by USMSFP researchers. The first set of functions used data from tanks 1, 9 and 12 of batch one from GCRL (GCRL-1, 9, 12); the second set of functions used data from tanks 2 and 11 of batch one from GCRL (GCRL-2, 11); the third set of functions used data from trials 8, 9 and 11 from the WMC (WMC-8, WMC-9, and WMC-11); the fourth set of functions used data from trial 14 from the OI (OI-14) ; and the fifth set of functions used data from trial 23 from the OI (OI-23). The reason data were aggregated from several trials is to run the regressions based on more data observations. The reason for the two groups of GCRL is the differences in water quality conditions and tank volumes explained earlier in this data section. The reason to do both individual regressions for OI-14 and OI-23 is the difference in stocking rate and season mentioned earlier in this data section.

Inventory Model

The next step in the economic modeling process addresses maximization of net revenue through production practice optimization. The inventory model, as an integral part of the Hanson-Posadas bioeconomic model mentioned in Chapter One, was built in an Excel spreadsheet to solve for the optimal harvesting week, the optimal size to be harvested, and the optimal number of crops per year to maximize net revenue per year for each set of data. This inventory model was based on a weekly period and kept track of weekly feed cost and revenue. A final harvesting was done at the end of a production cycle. The optimal solution was solved manually.

Critical assumptions for this model were as follows: 1) back-to-back production batches were made over a long time period; 2) sufficient quantities of post-larvae were available as needed for stocking; 3) the quantity of shrimp harvested was equal to the quantity of shrimp sold; 4) feed price and PL price were fixed; 5) historic average annual farm-gate prices from 2002 to 2006 were used; 6) weekly survival rate (the percentage of shrimp surviving at the end of each week) was fixed to be 99 percent through production, and then 98, 97, 96, 95, and 94 percent; and 7) production cost covered feed cost and Post Larvae cost.

The inventory model began a production period by purchasing and stocking a certain quantity of post-larvae (PL) shrimp. This variable was denoted by H_0 and was measured in PLs per cubic meter. Another variable Q_i kept track of the number of shrimp per cubic meter at the beginning or end of every week. For instance, Q_0 equaled H_0 at the beginning of the production period. Then Q_1 was the number of shrimp at the end of week one, and thus also at the beginning of week two, etc., for the entire production cycle.

The model must compute the number of shrimp per cubic meter that survive every week, as:

$$Q_i = v_i Q_{i-1} \tag{4-3}$$

where v_i was the weekly survival rate in %.

Now the model could calculate the average individual shrimp weight at the end of week i through the growth regression function as:

$$W_i = \beta_0 + \beta_1 * X + \beta_2 * (X)^2 \tag{4-4}$$

with all variables identified previously.

With all quantity and weight information at hand, the model was ready to compute costs and revenues. To compute revenue, a selling price was needed. P_j was the price ($/lb) for weight category j, where $j = 1, \ldots, 10$. The price for different shrimp size categories, P_j, was a discontinuous function of shrimp weight:

$$P_j = P_j(W_i) \tag{4-5}$$

where W_i was the weight per shrimp at the end of each week i. Revenue, R_i, was computed as:

$$R_i = P_j * W_i * H_i \tag{4-6}$$

where H_i was a decision variable denoting the number of shrimp sold at the end of week i. The quantity of feed fed per cubic meter during the week, F_i, was provided by the feed regression function:

$$F_i = \beta_0 + \beta_1 * X + \beta_2 * (X)^2 \tag{4-7}$$

The cost of feed consumed per cubic meter during the week, C_i, was:

$$C_i = p_F * F_i \tag{4-8}$$

where p_F was the price ($/lb) of feed. Net revenue for the week was the feed cost subtracted from revenue.

The one-time purchase cost of the post-larvae was computed by multiplying the price of PLs by the quantity purchased at the beginning of the production period (H_0):

$$C_{PL} = P_{PL} * H_0 \tag{4-9}$$

The model then computed the cumulative net revenue T_i from the beginning of the batch through the end of week i as:

$$T_i = \sum (R_i - C_i) - C_{PL} \tag{4-10}$$

The final step was to compute the average net revenue per week (A_i), which was the objective function to be maximized:

$$A_i = \frac{T_i}{i} \tag{4-11}$$

There were a number of constraints that needed to be considered. First, the number of shrimp remaining after harvest was the beginning inventory for the next week, and was computed as:

$$Q_{i+1} = Q_i - H_i \tag{4-12}$$

This value must be greater than or equal to zero. Also, Q_{n+1} must be zero to assure that all shrimp had been harvested, where n was the last week in the model.

The optimal harvesting week was obtained at the maximum value of the average weekly net revenue. Then the net revenue per year was calculated as the average weekly net revenue multiplied by 52 weeks (or the net revenue per batch multiplied by the number of batches per year). The optimal number of batches per year was calculated as 52 weeks divided by the optimal harvesting week. The optimal size of shrimp to be harvested was calculated by plugging in the optimal harvest week into the estimated growth function.

Price

Shrimp price from 1992 to 2001 mentioned in Chapter One came from the price reports by shrimp size categories by the NMFS (National Marine Fisheries Service). Feed price and PL price were provided by USMSFP researchers and private business quotes and were assumed to be fixed. Wholesale prices from 2002 to 2006 for wild, domestic white shrimp from the Gulf of Mexico were obtained on a monthly basis from the Urner Barry website through a paid subscription. Five years of monthly wholesale prices were collected and then averaged into five individual mean annual wholesale prices respectively for the years 2002 through 2006. However, these average annual wholesale prices needed to be "back" calculated into farm-gate prices (the price at which shrimp producers would sell their shrimp products). For this, it was assumed that a shrimp wholesaler would use a 30% mark-up over the price paid to a shrimp processor. A shrimp processor would use a 30% mark-up plus one dollar processing cost for each pound of shrimp purchased from farmers. Thus, the farm-gate shrimp price was calculated as:

$$P_{Farm\text{-}Gate} = P_{Wholesale} * (1 - 30\%) * (1 - 30\%) - 1 \tag{4-13}$$

where $P_{Farm\text{-}Gate}$ is the farm-gate price and $P_{Wholesale}$ is the wholesale price obtained from Urner Barry. Therefore, five individual farm-gate prices were calculated from five years of average annual wholesale prices, respectively. These five individual farm-gate prices were averaged into a mean price for the period from 2002 to 2006. For each year, ten farm-gate prices were calculated for ten shrimp size categories.

Each annual farm-gate price for 2002, 2003, 2004, 2005, and 2006 and the average annual farm-gate price for the five years were used in the inventory model to get the average weekly net revenue, the net revenue per year, and the net revenue from one batch for each year, respectively. Then, the maximum net revenue per year for WMC, GCRL, and OI were compared respectively using weekly survival rates of 99%, 98%, 97%, 96%, 95%, and 94%.

It is important to look at net revenue from price margins between size categories. Price margins between size categories were calculated as the price for the previous size category subtracted from the adjacent price for the current size category. Similarly, size margins were obtained between the two adjacent size categories. Price margins affect the net revenue.

In summary, this methodology chapter provided information on how data were used and manipulated, how regression estimates for the shrimp growth and feed functions were developed, how the building of the inventory model was accomplished, and how the shrimp price was calculated and analyzed. By use of the described procedures in this chapter, the next chapter, results, were obtained and discussed.

CHAPTER V

RESULTS AND DISCUSSION

This chapter is organized as follows: 1) growth and feed regression outputs; 2) analysis of optimal harvest strategy; and 3) analysis of historic shrimp pricing by size category and its effect on the optimal harvesting strategy.

Growth and Feed Regressions

Table 5.1 presents the individual shrimp growth regression output for GCRL, WMC, and OI, respectively. The coefficient of determination, R^2, for each of the five regressions in Table 5.1 was high, indicating that the estimates fit the data very well. In addition, the coefficient estimates of the quadratic terms were lower to the second decimal digit in terms of absolute value for GCRL and WMC. This implies that growth curves of GCRL and WMC were only a little curved. In other words, the curvature of the growth functions of GCRL and WMC was low. The reason is that during a growth period, a shrimp size would not shrink and it could attain a maximum weight and stopped. Seen from the data, average individual shrimp weight shrank a little sometimes (Figure 5.1). The reason could be that a small shrimp sample (about 20 to 25 shrimp) was randomly taken out from about 20,000 to be recorded at the end of each week. Also, a large size shrimp was more likely to die than a smaller size shrimp because the large shrimp would jump out of the tank and die on the floor or there was some reason researchers did not figure out yet. In addition, larger shrimp is hard to catch into the sampling net because they often jumped fast off the net. Thus, the sample randomly taken probably consisted of much smaller size shrimp due to death of larger shrimp or larger and faster shrimp escaping the sampling net.

Table 5.1 Regression Output for Individual Shrimp Growth

	Intercept	Week #	$(\text{Week } \#)^2$	# of Obs	R^2
GCRL-1,9,12	-0.6230	1.5450	-0.0234	54	0.9709
P-Value	-0.1890	0.0000	0.0002		
GCRL-2,11	-0.8766	1.6415	-0.0338	36	0.9654
P-Value	0.1422	0.0000	0.0000		
WMC-8,9,11	-2.9322	2.3807	-0.0559	48	0.9405
P-Value	0.0018	0.0000	0.0000		
OI-14	0.5571	1.5359	-0.0078	14	0.9896
P-Value	0.2586	0.0000	0.5417		
OI-23	-0.0307	1.3838	0.0124	30	0.9881
P-Value	0.9354	0.0000	0.1594		

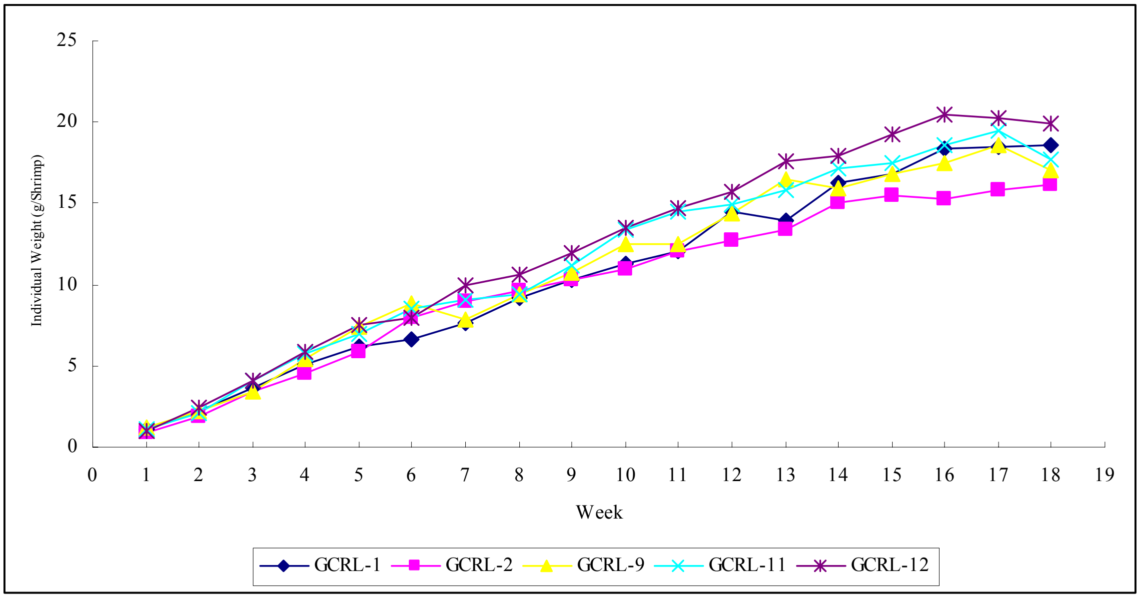

Figure 5.1 Average Individual Shrimp Weight for GCRL – 1, 2, 9, 11, and 12

However, the coefficient estimates of the quadratic term for OI 14 and OI 23 were non-significant, indicating that the average individual shrimp weight at the end of each week was a linear function of the week based on the data. Thus, linear function regressions of the individual shrimp growth were estimated for OI-14 and OI-23 again. Table 5.2 shows the output. These intercept and coefficient estimates of the growth functions were included as components of the inventory model.

Table 5.2 Regression Output for Individual Shrimp Growth for OI-14 and OI-23

	Intercept	Week #	# of Obs	R^2
OI-14	0.7600	1.4345	14	0.9892
P-Value	0.0402	0.0000		
OI-23	-0.4069	1.5575	30	0.9872
P-Value	0.1514	0.0000		

Seen from Table 5.3, average growth rates of GCRL were close to 1.0 g per week and those of WMC and OI were close to 1.5 g per week. This means that shrimp from GCRL had a lower growth rate than those from WMC and OI.

Table 5.3 Average Shrimp Growth Rate

Source	Avg. Growth Rate (g/week)	Source	Avg. Growth Rate (g/week)
GCRL-1	0.99	WMC-8	1.39
GCRL-2	0.86	WMC-9	1.46
GCRL-9	0.91	WMC-11	1.00
GCRL-11	0.94	OI-14	1.37
GCRL-12	1.07	OI-23	1.44

Table 5.4 presents the regression output of shrimp feed for GCRL, WMC, and OI. The R^2s were low for the two GCRL and WMC shrimp feed regressions. One of the reasons for the low R^2 could be that there were some outliers in the data for GCRL and WMC. Also, feed functions for GCRL and WMC were slightly concave, meaning that the quantity of feed reached a maximum peak and then declined. The reasons could be as follows: 1) some large size shrimp died as mentioned before in this section; 2) lower water quality (such as high nitrite or low oxygen levels) could affect shrimp's appetite; 3) shrimp can eat the microorganism which can be nourished by feeding in the tank (Chapter Two); and 4) the quantity of feed should be controlled, otherwise too much feed could pollute tank water and cause shrimp stress and susceptibility to diseases. Although OI-14 had high R^2 values, the estimate of the quadratic term was again non-significant.

The non-significant estimate shows that the quantity of feed fed per cubic meter per week was a linear function of the week based on the data.

Table 5.4 Regression Output for Shrimp Feed

	Intercept	Week #	$(\text{Week \#})^2$	# of Obs	R^2
GCRL-1,9,12	61.7075	110.5323	-4.6320	54	0.5268
P-Value	0.3955	0.0000	0.0000		
GCRL-2,11	91.2295	91.4321	-4.0453	36	0.6804
P-Value	0.0737	0.0000	0.0000		
WMC-8,9,11	197.5832	150.9538	-7.1567	47	0.4179
P-Value	0.1367	0.0000	0.0000		
OI-14	240.4254	199.9677	-5.9431	12	0.8595
P-Value	0.2745	0.0230	0.3057		
OI-23	28.9853	35.1688	-1.1946	14	0.9076
P-Value	0.2530	0.0006	0.0295		

Thus, linear function regression of shrimp feed was estimated for OI-14 again and Table 5.5 shows the result. Also, the coefficient estimate of the linear term for OI-23 was much lower than that of OI-14, GCRL, and WMC. One possible reason is that the quantity of feed fed can be affected by climate, temperature, or water quality. These intercept and coefficient estimates of the feed functions were included as components of the inventory model.

Table 5.5 Regression Output for Shrimp Feed for OI-12

	Intercept	Week #	# of Obs	R^2
OI-14	420.6991	122.7076	12	0.8411
P-Value	0.0069	0.0000		

Analysis of Optimal Strategy

Since the objective was to maximize net revenue per year, the optimal strategy was the corresponding harvesting week when the maximum value of the average weekly net revenue was obtained. Then, net revenue per year can be calculated as the average weekly net revenue multiplied by 52 weeks. Also, the optimal number of crops per year was calculated as 52 weeks divided by the optimal harvesting week. In addition, the optimal shrimp size was calculated by plugging in the optimal harvesting week into the growth function. Table 5.6 shows the optimal harvesting week solutions for WMC, GCRL, and OI, and Table 5.7 presents the annual net revenue for each system under varying survival percentage ranging from 99% down to 94%. WMC 8, 9 and 11 had the same optimal harvesting week of twelve. The reason is that the same growth function was applied to WMC 8, 9, and 11 due to the aggregated data used in the regression estimates for the three trials. In addition, WMC 8, 9, and 11 had different net revenue because of different stocking rates. GCRL 1, 9, and 12 had a different growth function from GCRL 2 and 11. The former had an optimal harvesting week of seventeen, and the latter had an optimal harvesting week of fourteen. OI-14 and OI-23 had the optimal harvesting week of twelve and fourteen, respectively.

Table 5.6 The Optimal Strategy when Shrimp Price is the Average Annual Price from 2002 to 2006 and Weekly Survival Rate is 99%

Source	Stocking Rate (Shrimp/m^3)	Optimal Harvest Week	Average Annual NR (\$/m^3.year)	Optimal Harvesting Size (g)	Price (\$/lb)	Optimal # of Crops Per Year (#)
OI-23	301	14	49.59	21.40	1.94	3.71
(# per lb)				(20 - 25)		
WMC-11	371	12	56.94	18.58	1.94	4.33
(# per lb)				(20 - 25)		
GCRL-1,9,12	401	17	42.58	18.87	1.94	3.06
(# per lb)				(20 - 25)		
GCRL-2,11	401	14	22.17	15.48	1.49	3.71
(# per lb)				(25 - 30)		
WMC-8	420	12	67.64	18.58	1.94	4.33
(# per lb)				(20 -25)		
WMC-9	450	12	74.19	18.58	1.94	4.33
(# per lb)				(20 - 25)		
OI-14	705	12	63.87	17.97	1.49	4.33
(# per lb)				(25 - 30)		

When the survival rate decreased, the optimal harvest week did not change for the seven source runs. However, as seen in Table 5.7, the annual net revenues were negatively affected as survival decreased. One of the GCRL runs began to have negative annual net revenue at the 96% survival level. Thus, high survival rates are necessary for positive net revenue revenues in some cases.

Table 5.7 Maximum Annual Net Revenues

Source	Stocking Rate	Annual Net Revenue with Varying Weekly Survival Rate (%)					
		99%	98%	97%	96%	95%	94%
	(Shrimp/m^3)	(\$/m^3.Year)	(\$/m^3.Year)	(\$/m^3.Year)	(\$/m^3.Year)	(\$/m^3.Year)	(\$/m^3.Year)
OI-23	301	60.62	48.84	38.53	29.51	21.63	14.76
WMC-11	371	56.94	43.94	32.33	21.97	12.74	4.51
GCRL-1,9,12	401	42.58	29.33	18.11	8.6	0.52	-6.3
GCRL-2,11	401	22.17	13.45	5.79	-0.85	-6.72	-11.77
WMC-8	420	67.64	52.95	39.82	28.08	17.59	8.28
WMC-9	450	74.19	58.46	44.37	31.81	20.58	10.62
OI-14	705	63.87	45.53	29.14	14.50	1.45	-10.17

Figure 5.2 shows the net revenue per year for WMC, GCRL, and OI respectively. For each trial, the annual net revenue attained the maximum value at the optimal harvesting week. Also, all of the net revenue curves have a step-like character due to the shrimp price margin leaps among shrimp size categories. For WMC and GCRL, each annual net revenue curve goes upward at first and then downward after they reach the maximum point at week twelve. For OI 14 and OI 23 trials, however, the annual net revenue curves always go upward and then end up at the maximum point. The reason is that the estimated growth and feed functions for WMC and GCRL were concave quadratic functions, and the estimated growth and feed functions for OI were linear functions. These linear growth and feed estimates did not fit well with the concave growth and feed curves of empirical studies. Whether an optimal harvesting week occurs after the end of the twelve or fourteen week growth period is unknown. For each trial of WMC, the break-even point occurs at the seventeenth week. This means that shrimp

should be harvested no earlier than at the end of week seven to cover the feed and PL costs. For GCRL and OI, the break-even points occur when the harvesting week is between ten and eleven and between eight and nine weeks, respectively (Figure 5.2).

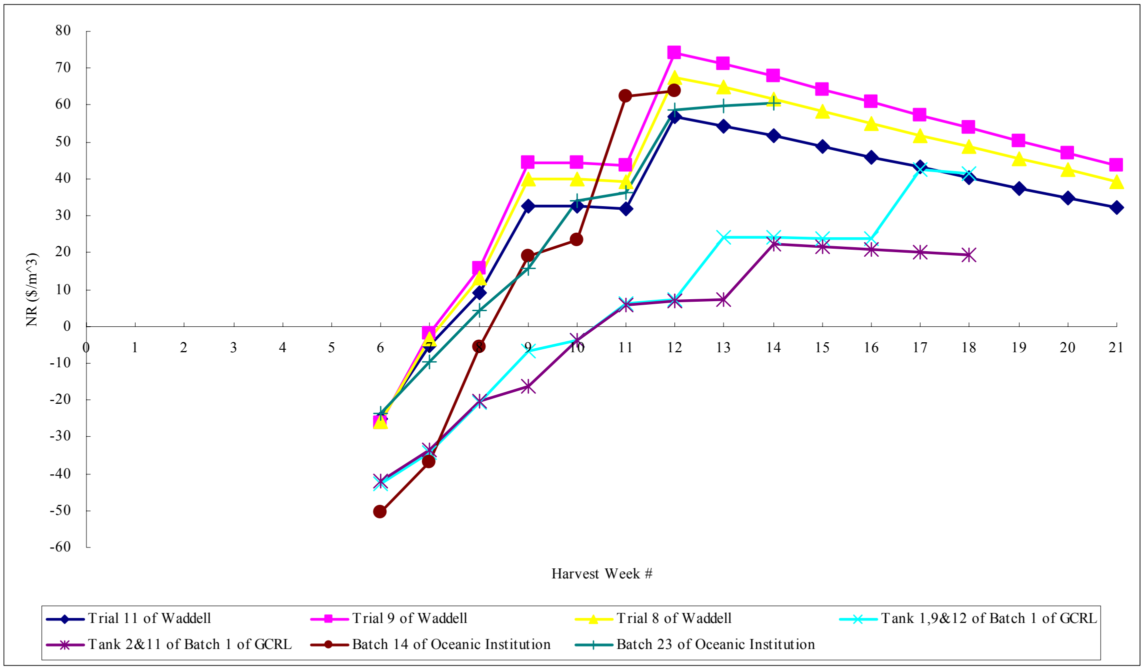

Figure 5.2 Comparison of Annual Net Revenue of Shrimp Harvested per Cubic Meter for Waddell, GCRL and the Oceanic Institute when the Weekly Survival Rate is 99% and Shrimp Price is the Average Annual Price from 2002 to 2006.

At the optimal harvesting week, the relevant net revenue from one batch could not be the maximum value, as discussed earlier in conceptual framework chapter of this thesis. Comparing Figure 5.2 with Figure 5.3, it can be seen that optimal harvest week may change when annual net revenue is disregarded and only one batch is considered. For example, the maximum net revenue from one batch occurred at harvest week seventeen instead of the optimal twelfth week for WMC in the annual net revenue case.

Detailed comparison between the annual net revenue and net revenue from one batch per year among WMC 8, 9, and 11 can be found in Figures 5.4, 5.5, and 5.6, respectively. In Figure 5.4 (WMC 11), different optimal harvest weeks can be seen, at week twelve for the annual net return and at week sixteen-seventeen for the one batch net revenue. Similar differences in harvest weeks can be seen in Figure 5.7 (GCRL-1, 9, 12) and Figure 5.8 (GCRL-2, 11). Likewise, seen from Figure 5.7 and Figure 5.8, the maximum net revenue from one batch occurred at harvest week of nineteen instead of the optimal week seventeen for GCRL-1, 9, 12 and occurred at harvest week nineteen instead of the optimal week fourteen for GCRL-2, 11.

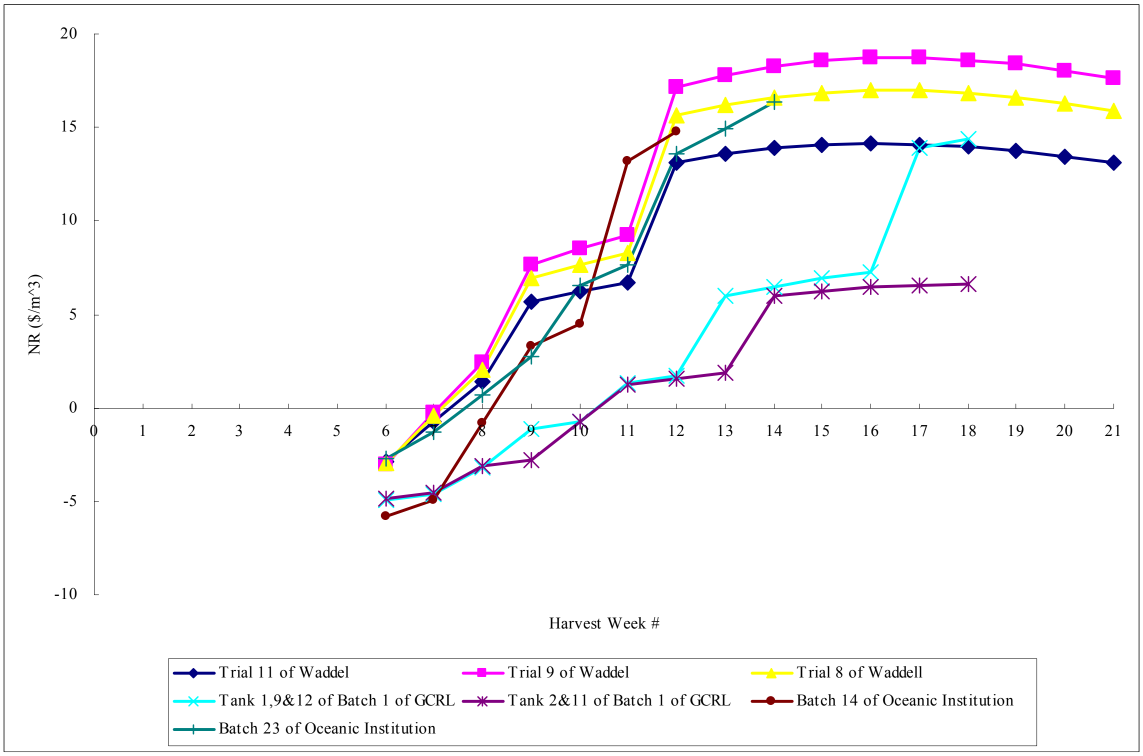

Figure 5.3 Comparison of the Net Revenue from One Batch of Shrimp Harvested per Cubic Meter for Waddell, GCRL and the Oceanic Institute when the Weekly Survival Rate is 99% and Shrimp Price is the Average Annual Price from 2002 to 2006.

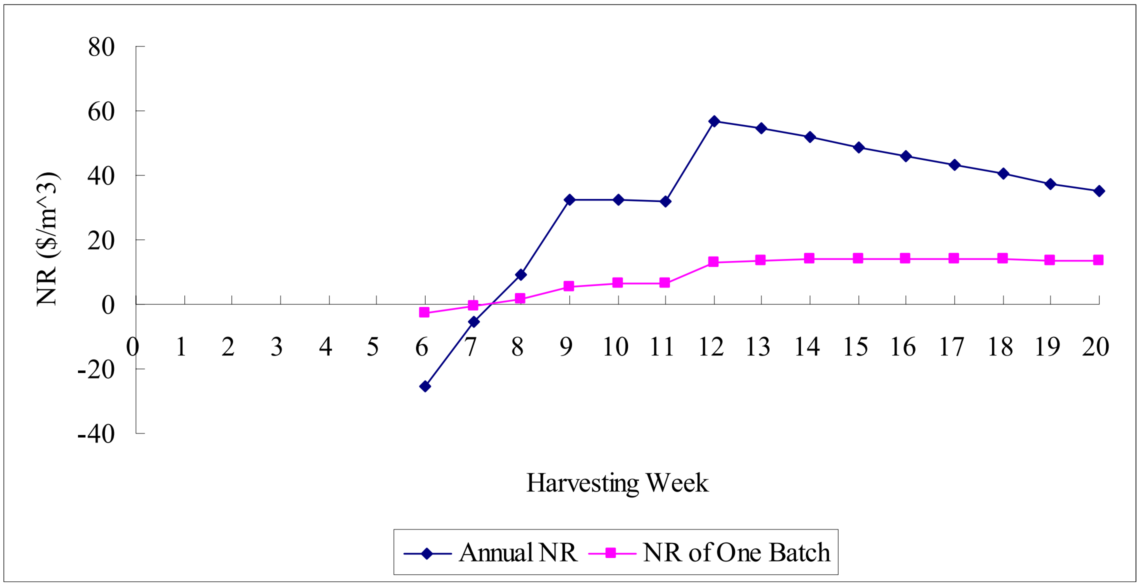

Figure 5.4 Comparison of Annual Net Revenue and Net Revenue from One Batch for Waddell 11 when Shrimp Price was the Average Annual Price from 2002 to 2006 and the Weekly Survival Rate is 99%.

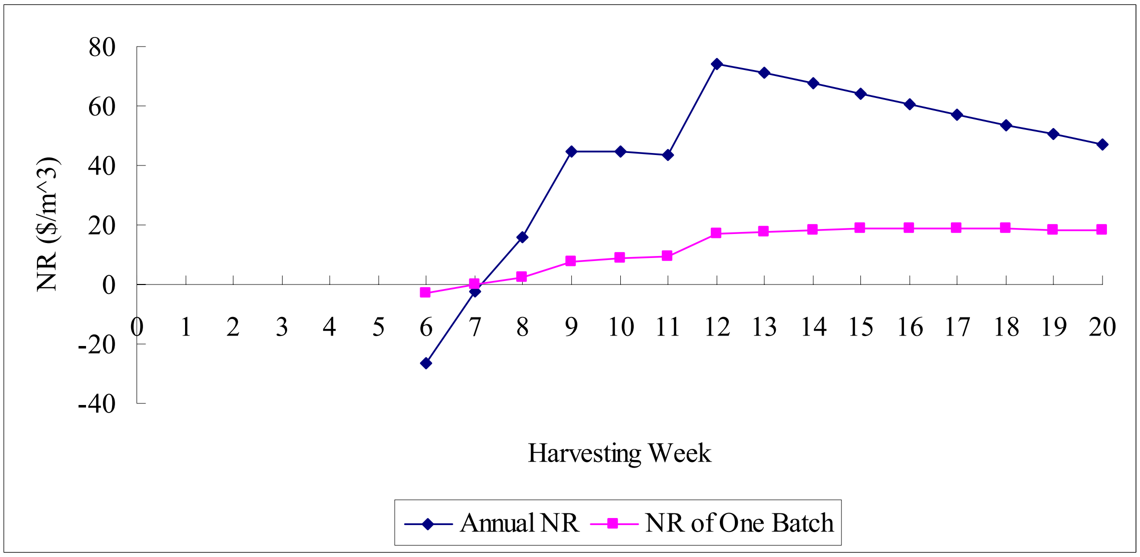

Figure 5.5 Comparison of Annual Net Revenue and Net Revenue from One Batch for Waddell 9 when Shrimp Price is the Average Annual Price from 2002 to 2006 and the Weekly Survival Rate is 99%.

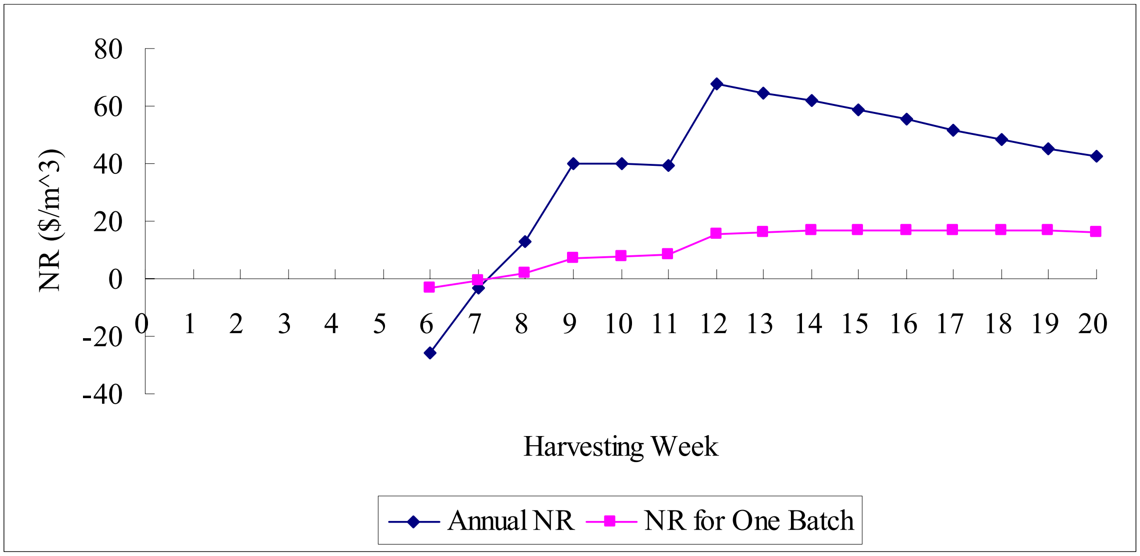

Figure 5.6 Comparison of Annual Net Revenue and Net Revenue from One Batch for Waddell 8 when Shrimp Price is the Average Annual Price from 2002 to 2006 and the Weekly Survival Rate is 99%.

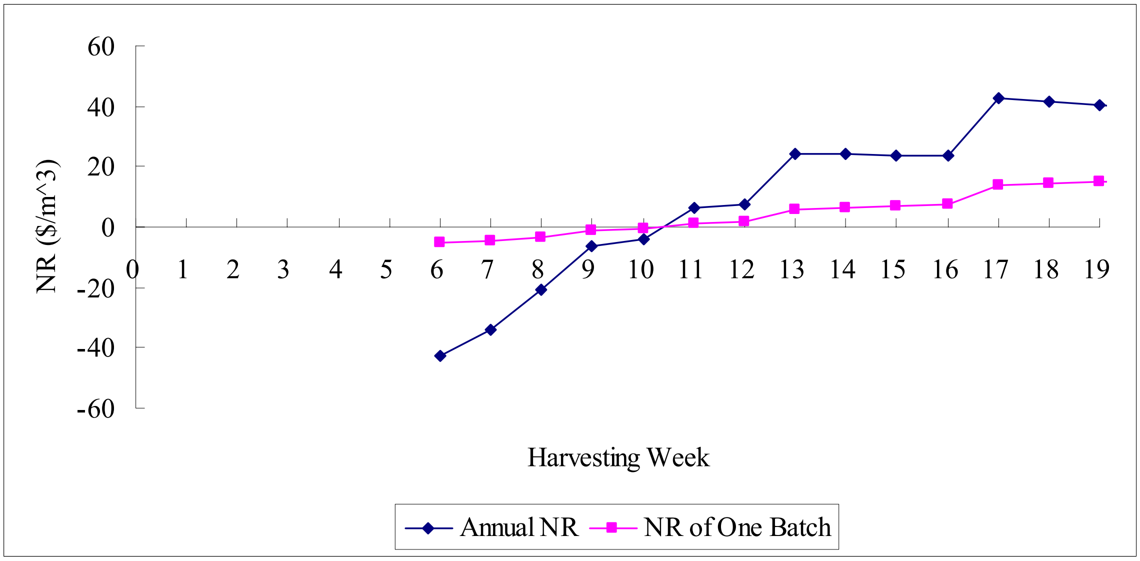

Figure 5.7 Comparison of Annual Net Revenue and Net Revenue from One Batch for GCRL 1, 9, and 12 when Shrimp Price is the Average Annual Price from 2002 to 2006 and the Weekly Survival Rate is 99%.

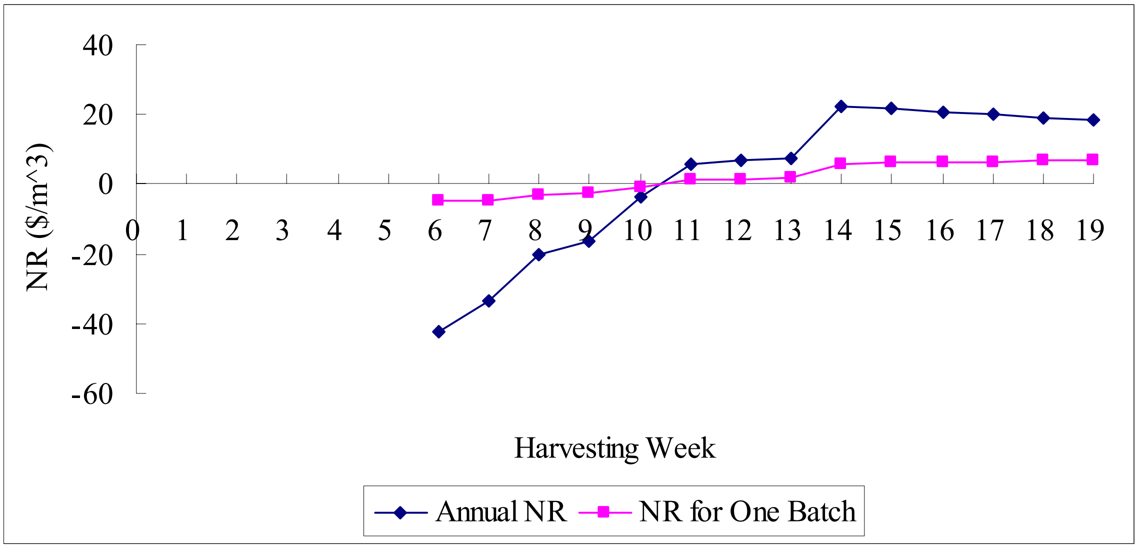

Figure 5.8 Comparison of Annual Net Revenue and Net Revenue from One Batch for GCRL 2 and 11 when Shrimp Price is the Average Annual Price from 2002 to 2006 and the Weekly Survival Rate is 99%.

For GCRL, WMC, and OI when weekly survival rate decreased from 99% to 98%, 97%, 96%, 95%, and 94%, the net revenue per year or the average weekly net revenue fell while the optimal harvesting week, number of crops per year, and harvesting size remained the same. Thus, weekly survival rate did not change the optimal solution but did change the value of the objective function (i.e., the average weekly net revenue or the annual net revenue).

Figure 5.9 indicates that the average weekly net revenue goes positively upward as the weekly survival rate increases. The slope of the curve for OI-14 is greater than that of other curves. There are two reasons: 1) OI-14 had a stocking rate of 705 shrimp per m^3, much higher than those of others; and 2) the growth function was linear and the optimal harvesting week occurred at the end of the growth period. Thus, the output and revenue of OI-14 was higher than those of other trials. Seen from the Figure 5.9, the break-even points are approximately 94% (WMC 8, 9, and 11), 95% (GCRL 1, 9, and 12), and 96% (GCRL 2 and 11) respectively. Also, for OI 14 and 23, the break-even points could be lower than 93%. Thus, only when the survival rate attains the break-even point, can the cost be covered by revenue. Therefore, maintaining a high weekly survival rate is an effective way to gain more net revenue.

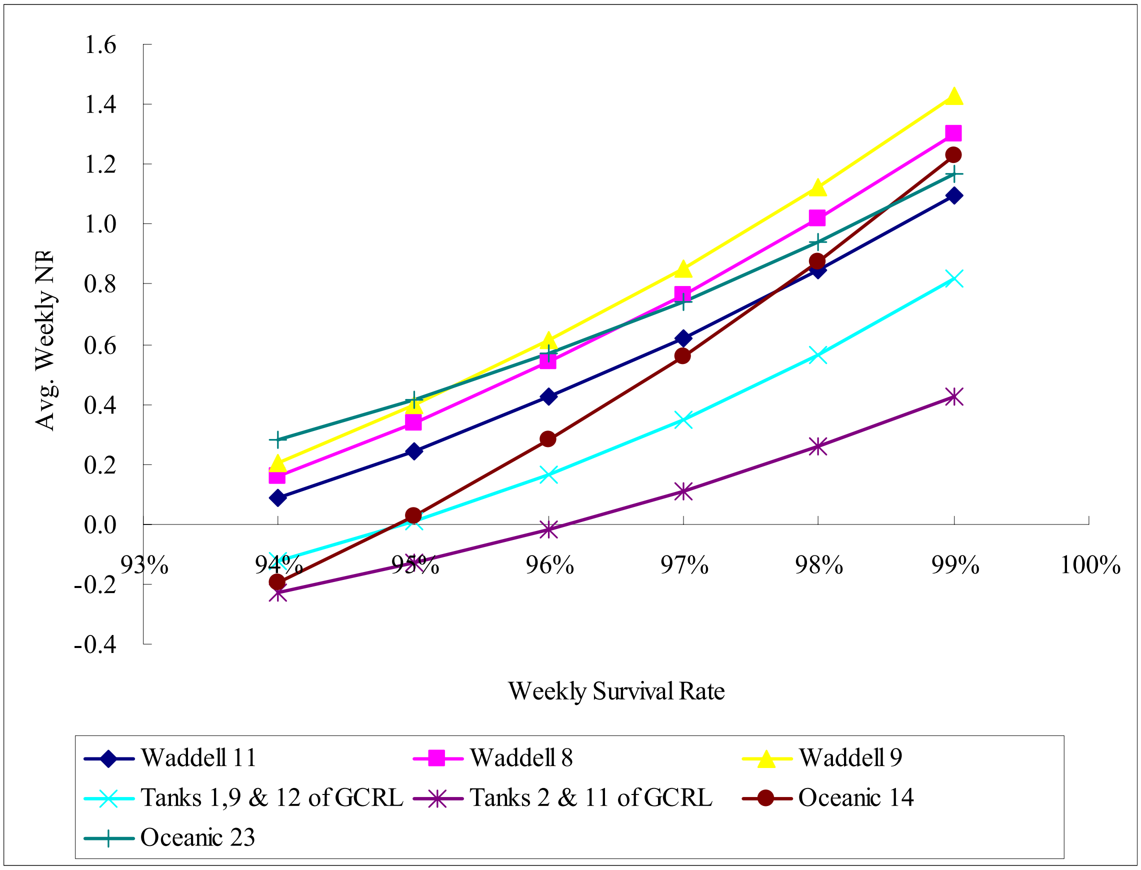

Figure 5.9 Sensitivity Analysis of the Average Weekly Net Revenue Per m^3 when the Shrimp Price is the Average Annual Price from 2002 to 2006

Analysis of Shrimp Price Margins

Table 5.8 and Figure 5.10 show the farm-gate prices by ten shrimp size categories from 2002 to 2006. Shrimp prices were on a downward trend during this period for size categories. The reason for this trend is the greater quantity of shrimp supply from foreign countries as mentioned in Chapter One.

Table 5.8 Farm-Gate Shrimp Prices by Size Categories

Size				Price ($/lb)					
(#/lb)	(g/shrimp)		(g/shrimp)	2002-06 Avg.	2002	2003	2004	2005	2006
under 15		>	30.24	2.51	3.09	2.51	2.42	2.52	2.03
15-20	30.24	-	22.68	2.51	3.09	2.51	2.42	2.52	2.03
20-25	22.68	-	18.14	1.94	2.32	2.02	2.16	1.82	1.37
25-30	18.14	-	15.12	1.49	1.66	1.51	1.68	1.43	1.18
30-35	15.12	-	12.96	1.16	1.25	1.35	1.08	1.07	1.07
35-40	12.96	-	11.34	1.00	1.13	1.11	0.93	0.94	0.90
40-50	11.34	-	9.07	0.81	0.93	0.92	0.62	0.82	0.75
50-60	9.07	-	7.56	0.67	0.82	0.74	0.49	0.61	0.65
60-70	7.56	-	6.48	0.55	0.62	0.56	0.41	0.54	0.59
70-80	6.48	-	5.67	0.44	0.51	0.44	0.35		0.42
80-90	5.67	-	5.04	0.34	0.40	0.34	0.25		

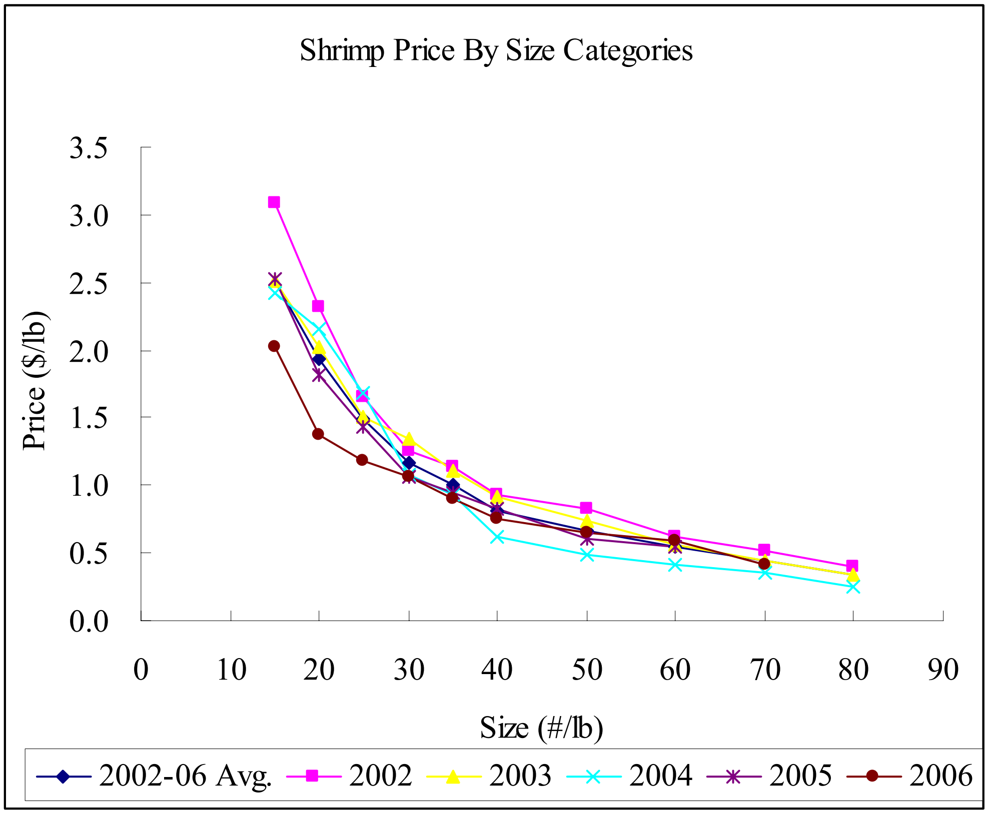

Figure 5.10 Farm-Gate Shrimp Prices by Size Categories

The optimal harvest week strategies for WMC, GCRL, and OI did not change when the individual average annual prices (2002-2006) and five-year average annual prices were used, Table 5.9 (WMC-11), Table 5.10 (WMC-8), Table 5.11 (WMC-9), Table 5.12 (GCRL-1, 9, 12), Table 5.13 (GCRL-2, 11), Table 5.14 (OI-14), and Table 5.15 (OI-23). Graphically, Figure 5.11 through 5.17 present the annual net revenue for each trial with the 2002 to 2006 annual average price, maximum annual net revenue achieved, and corresponding harvest week. Note that the harvest week does not change but the breakeven week is greater for the lower annual prices. This means that the optimal harvesting week was the same, as were the relevant number of crops per year and the harvest size. This implies that price does not change the optimal harvest week solution but does change the value of the objective function i.e., the average weekly net revenue and the annual net revenue.

Table 5.9 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 11) when Weekly Survival Rate is 99% and Stocking Rate is 371 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($/$m^3$)	Maximum Avg. Weekly NR ($/$m^3$)	Maximum Annual NR ($/$m^3$.year)
2002	2.32	12	18.58	18.26	1.52	79.12
2003	2.02	12	18.58	14.22	1.18	61.61
2004	2.16	12	18.58	16.10	1.34	69.78
2005	1.82	12	18.58	11.52	0.96	49.94
2006	1.37	12	18.58	5.46	0.46	23.67
5 Year Average	1.94	12	18.58	13.14	1.10	56.94

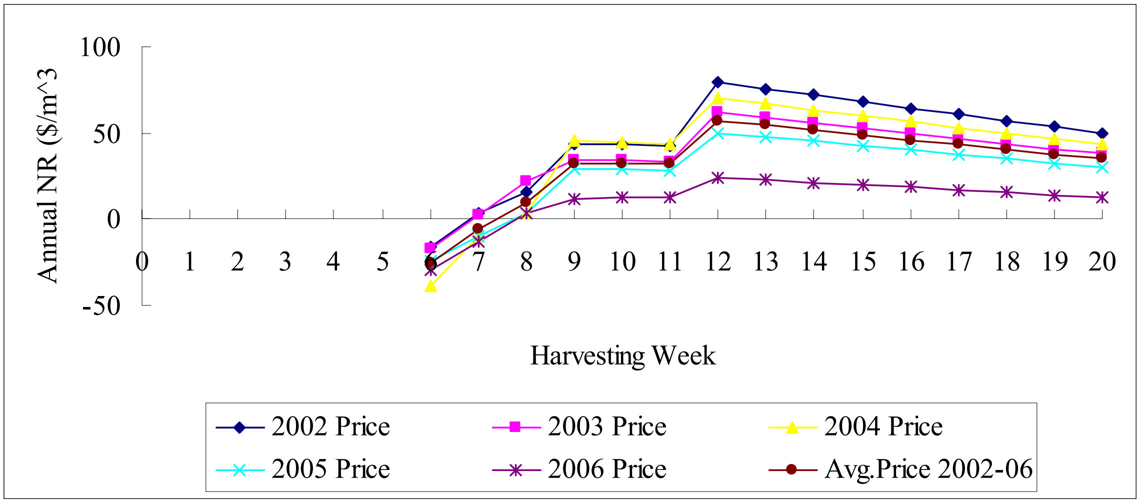

Figure 5.11 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 11) when Weekly Survival Rate is 99% and Stocking Rate is 371 Shrimp per m^3

Table 5.10 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 8) when Weekly Survival Rate is 99% and Stocking Rate is 420 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($/$m^3$)	Maximum Avg. Weekly NR ($/$m^3$)	Maximum Annual NR ($/$m^3$.year)
2002	2.32	12	18.58	21.40	1.78	92.75
2003	2.02	12	18.58	16.83	1.40	72.93
2004	2.16	12	18.58	18.97	1.58	82.18
2005	1.82	12	18.58	13.78	1.15	59.72
2006	1.37	12	18.58	6.92	0.58	29.99
5 Year Average	1.94	12	18.58	15.61	1.30	67.65

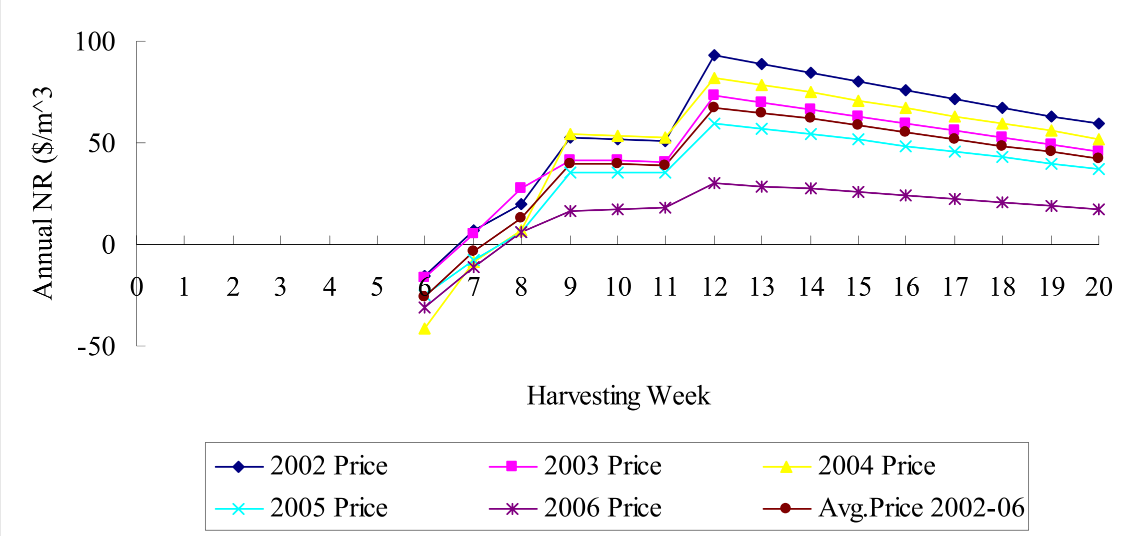

Figure 5.12 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 8) when Weekly Survival Rate is 99% and Stocking Rate is 420 Shrimp per m^3

Table 5.11 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 9) when Weekly Survival Rate is 99% and Stocking Rate is 450 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($\$/m^3$)	Maximum Avg. Weekly NR ($\$/m^3$)	Maximum Annual NR ($\$/m^3$.year)
2002	2.32	12	18.58	23.33	1.94	101.10
2003	2.02	12	18.58	18.43	1.54	79.87
2004	2.16	12	18.58	20.72	1.73	89.78
2005	1.82	12	18.58	15.16	1.26	65.71
2006	1.37	12	18.58	7.81	0.65	33.85
5 Year Average	1.94	12	18.58	17.12	1.43	74.20

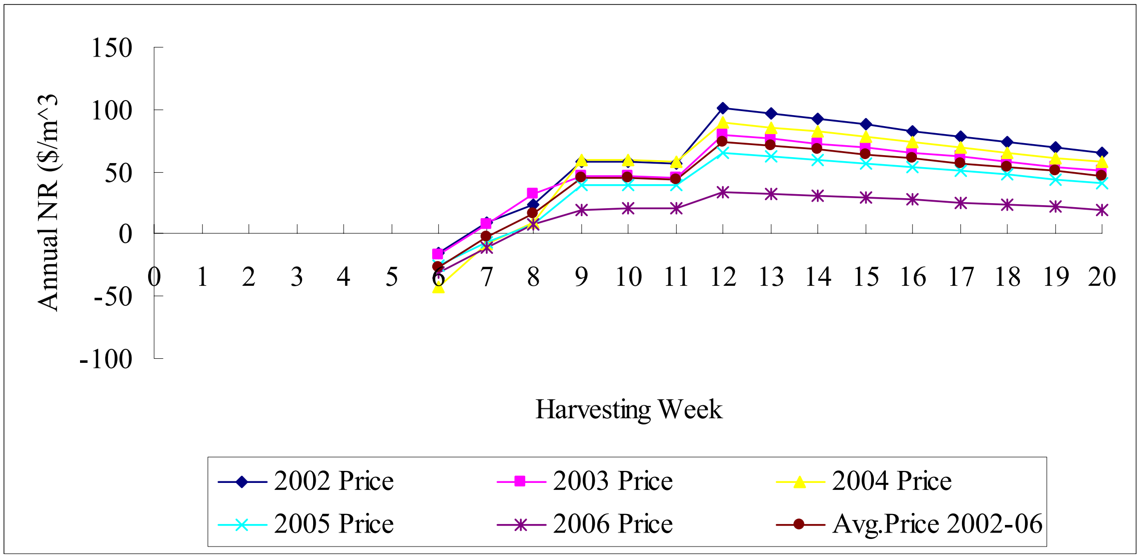

Figure 5.13 Sensitivity Analysis of Net Revenue on Price for Waddell (Trial 9) when Weekly Survival Rate is 99% and Stocking Rate is 450 Shrimp per m^3

Table 5.12 Sensitivity Analysis of Net Revenue on Price for Tanks 1, 9, and 12 of Batch 1 of GCRL when Weekly Survival Rate is 99% and Stocking Rate is 401 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($/$m^3$)	Maximum Avg. Weekly NR ($/$m^3$)	Maximum Annual NR ($/$m^3$.year)
2002	2.32	17	18.87	19.26	1.13	58.91
2003	2.02	17	18.87	15.04	0.88	46.01
2004	2.16	17	18.87	17.01	1.00	52.03
2005	1.82	17	18.87	12.23	0.72	37.41
2006	1.37	17	18.87	5.90	0.35	18.05
5 Year Average	1.94	17	18.87	13.92	0.82	42.57

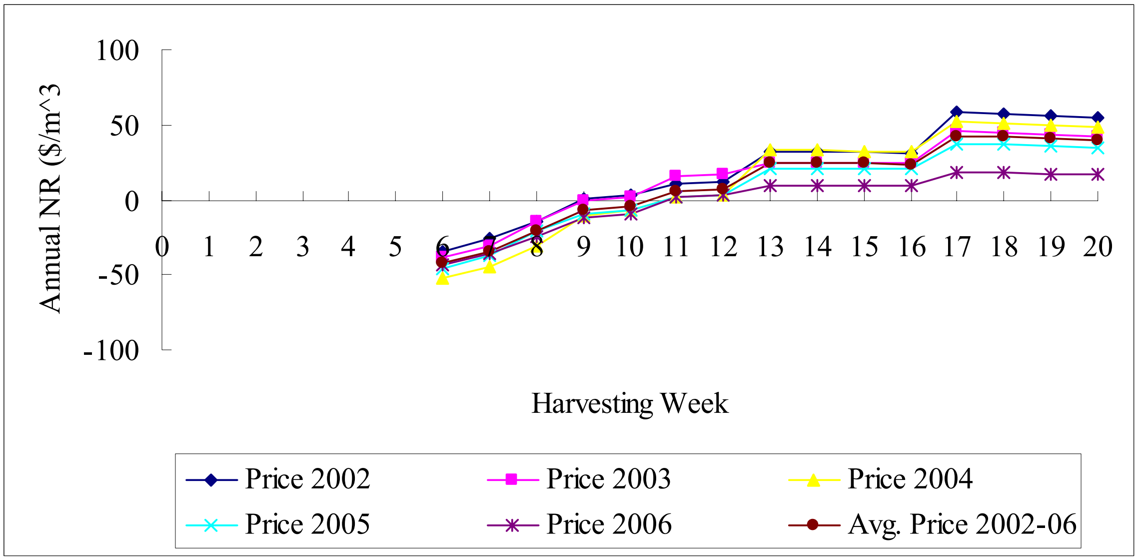

Figure 5.14 Sensitivity Analysis of Net Revenue on Price for Tanks 1, 9, and 12 of Batch 1 of GCRL when Weekly Survival Rate is 99% and Stocking Rate is 401 Shrimp per m^3

Table 5.13 Sensitivity Analysis of Net Revenue on Price for Tanks 2 and 11 of Batch 1 of GCRL when Weekly Survival Rate is 99% and Stocking Rate is 401 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($/m^3)	Maximum Avg. Weekly NR ($/m^3)	Maximum Annual NR ($/m^3.year)
2002	1.66	14	15.48	7.99	0.57	29.68
2003	1.51	14	15.48	6.21	0.44	23.05
2004	1.68	14	15.48	8.23	0.59	30.56
2005	1.43	14	15.48	5.25	0.38	19.52
2006	1.18	14	15.48	2.28	0.16	8.47
5 Year Average	1.49	14	15.48	5.97	0.43	22.17

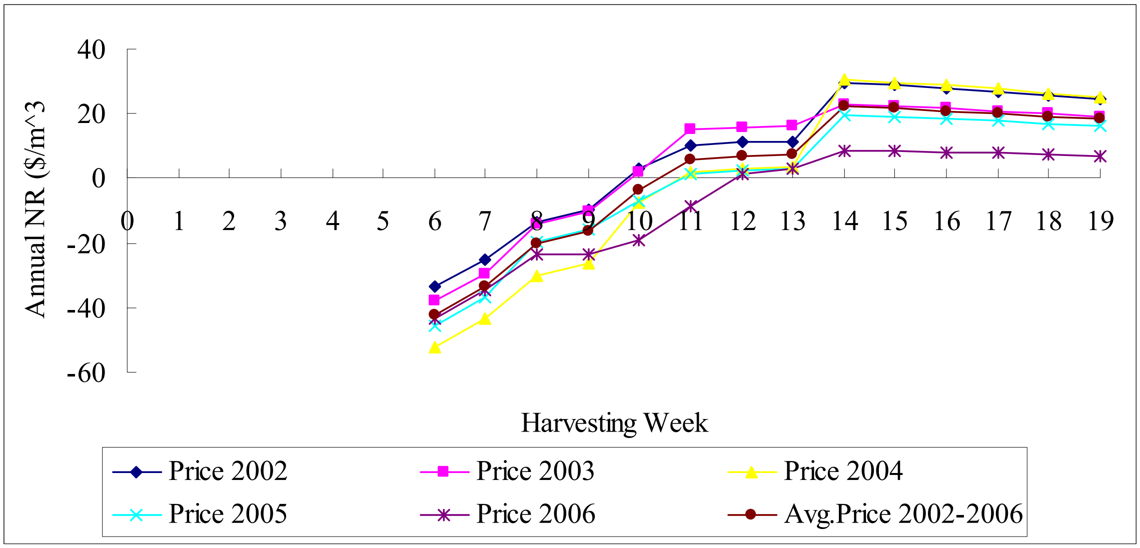

Figure 5.15 Sensitivity Analysis of Net Revenue on Price for Tanks 2 and 11 of Batch 1 of GCRL when Weekly Survival Rate is 99% and Stocking Rate is 401 Shrimp per m^3

Table 5.14 Sensitivity Analysis of Net Revenue on Price for Trial 14 of the Oceanic Institute when Weekly Survival Rate is 99% and Stocking Rate is 705 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($\$/m^3$)	Avg. Weekly NR ($\$/m^3$)	Annual NR ($\$/m^3$.year)
2002	2.32	12	17.97	18.95	1.58	82.11
2003	2.02	12	17.97	15.23	1.27	66.01
2004	2.16	12	17.97	19.44	1.62	84.25
2005	1.82	12	17.97	11.80	1.07	55.78
2006	1.37	12	17.97	7.06	0.59	30.60
5 Year Average	1.94	12	17.97	14.74	1.23	63.87

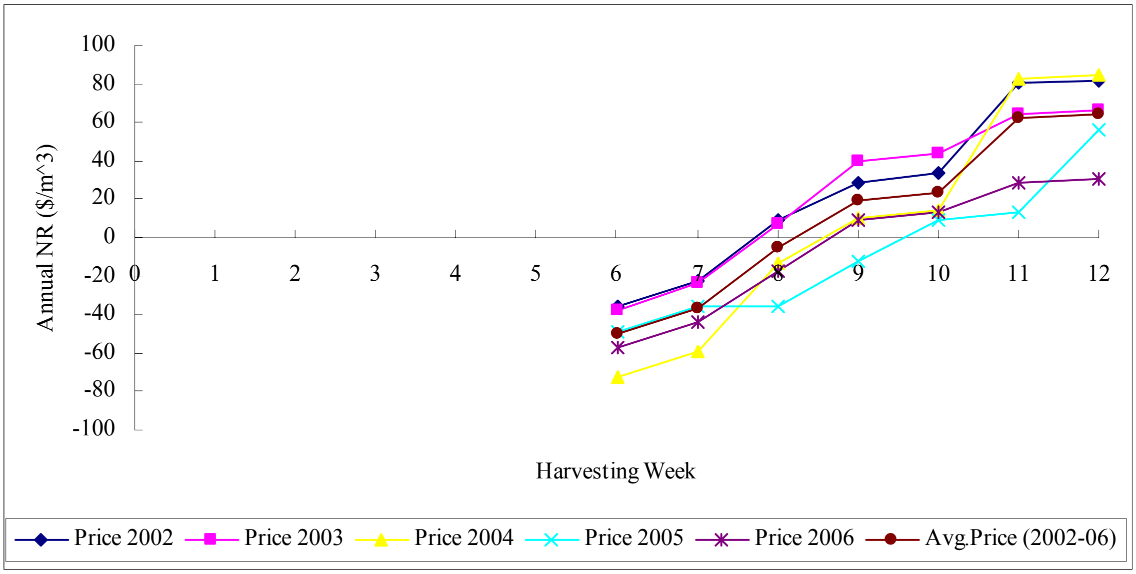

Figure 5.16 Sensitivity Analysis of Net Revenue on Price for Trial 14 of the Oceanic Institute when Weekly Survival Rate is 99% and Stocking Rate is 705 Shrimp per m^3

Table 5.15 Sensitivity Analysis of Net Revenue on Price for Trial 23 of the Oceanic Institute when Weekly Survival Rate is 99% and Stocking Rate is 301 Shrimp per m^3

Year	Average Annual Price ($/lb)	Optimal Harvest Week (#)	Optimal Harvest Size (g)	NR Per Batch ($\$/m^3$)	Avg. Weekly NR ($\$/m^3$)	Annual NR ($\$/m^3$.year)
2002	2.32	14	21.40	21.01	1.50	78.03
2003	2.02	14	21.40	17.31	1.24	64.28
2004	2.16	14	21.40	19.03	1.36	70.70
2005	1.82	14	21.40	14.84	1.06	55.12
2006	1.37	14	21.40	9.29	0.66	34.50
5 Year Average	1.94	14	21.40	16.32	1.17	60.62

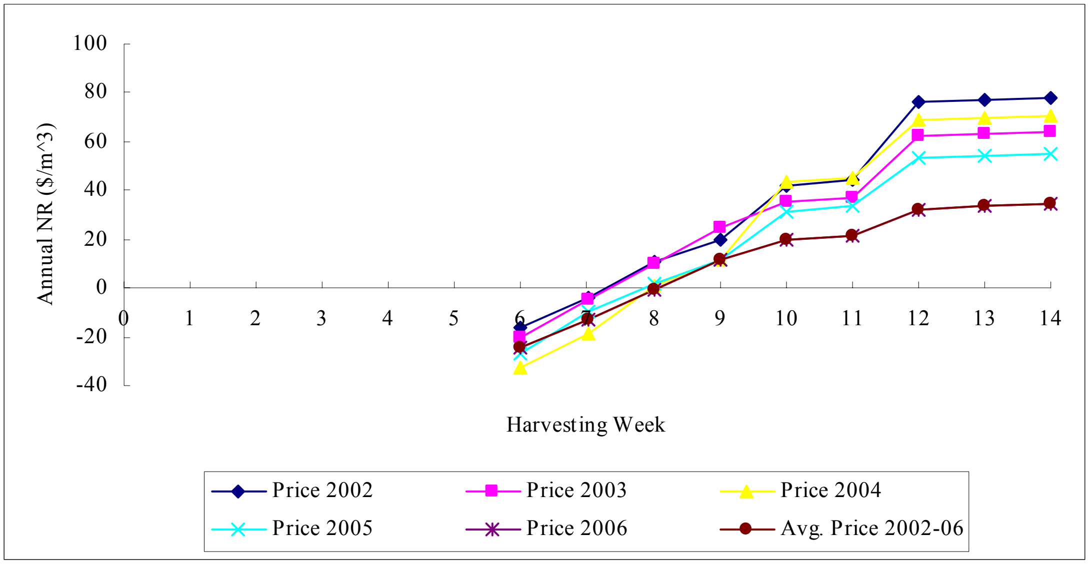

Figure 5.17 Sensitivity Analysis of Net Revenue on Price for Trial 23 of the Oceanic Institute when Weekly Survival Rate is 99% and Stocking Rate is 301 Shrimp per m^3

Within the same size category, shrimp should be harvested and sold at the end of the first week when shrimp grow into the weight range. The reason is that if the shrimp keep growing, cost will increase but price remains the same within the same size category. Seen from Figures 5.18, 5.19, 5.20, 5.21, and 5.22 each optimal harvesting week occurred at the end of the first week of the higher price range associated with the larger size shrimp. In Figure 5.18, for example, the optimal harvesting week twelve happened at the end of the first week of the higher price range, i.e., when shrimp reached 18.58 grams (21-25 #/lb).

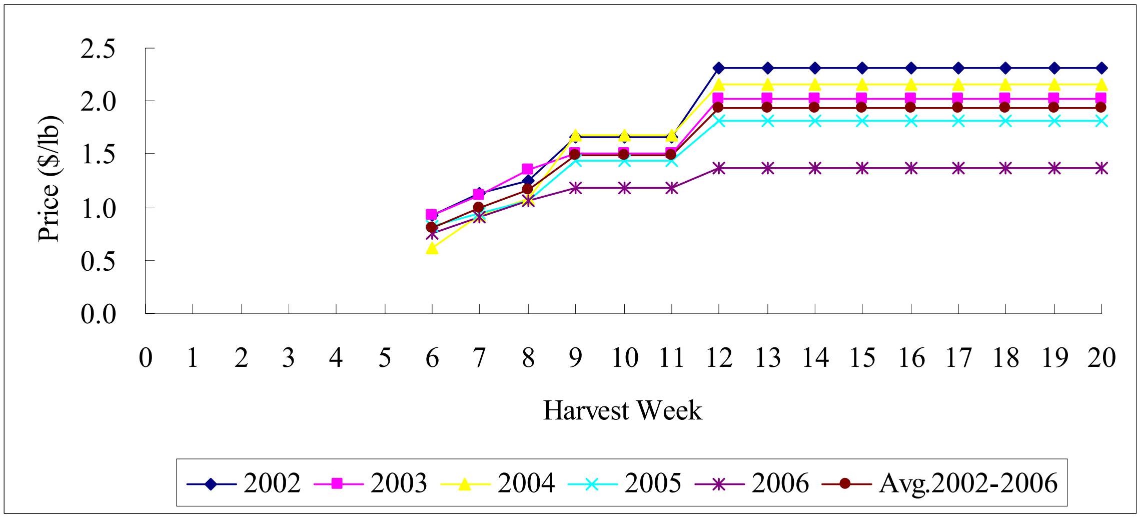

Figure 5.18 Price Relevant to Harvest Week for Trial 11 of Waddell

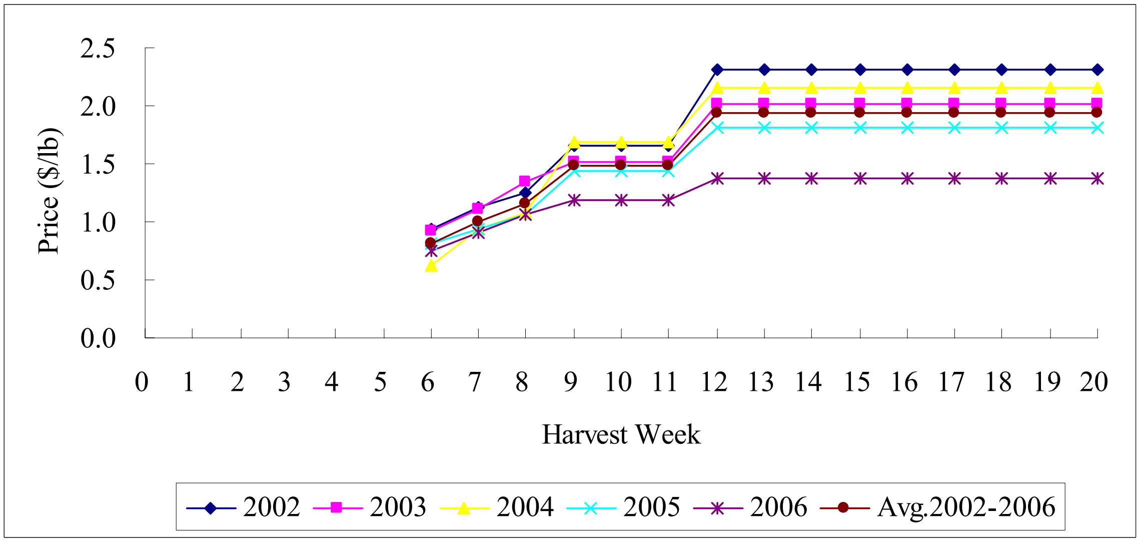

Figure 5.19 Price Relevant to Harvest Week for Trial 9 of Waddell

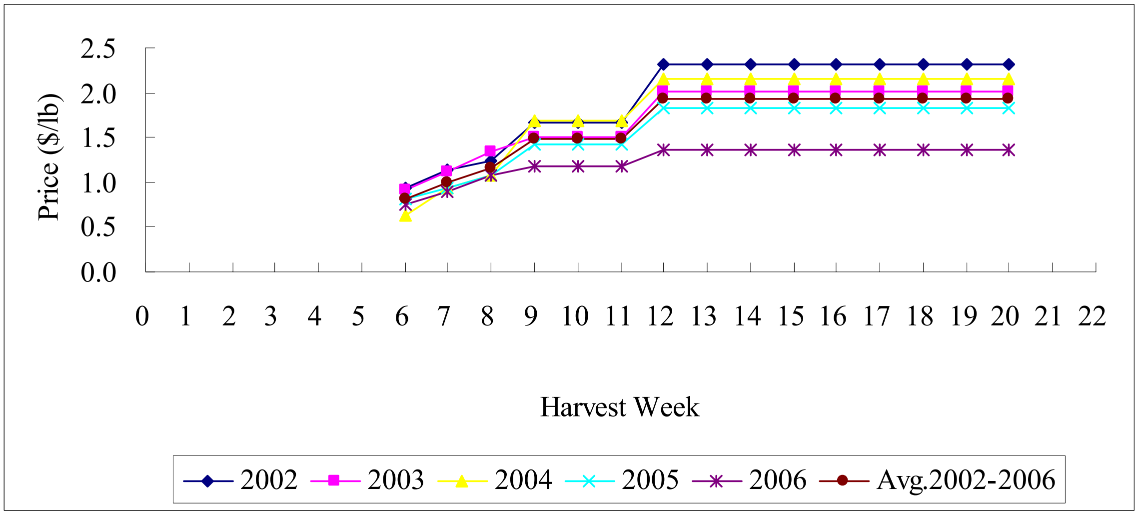

Figure 5.20 Price Relevant to Harvest Week for Trial 8 of Waddell

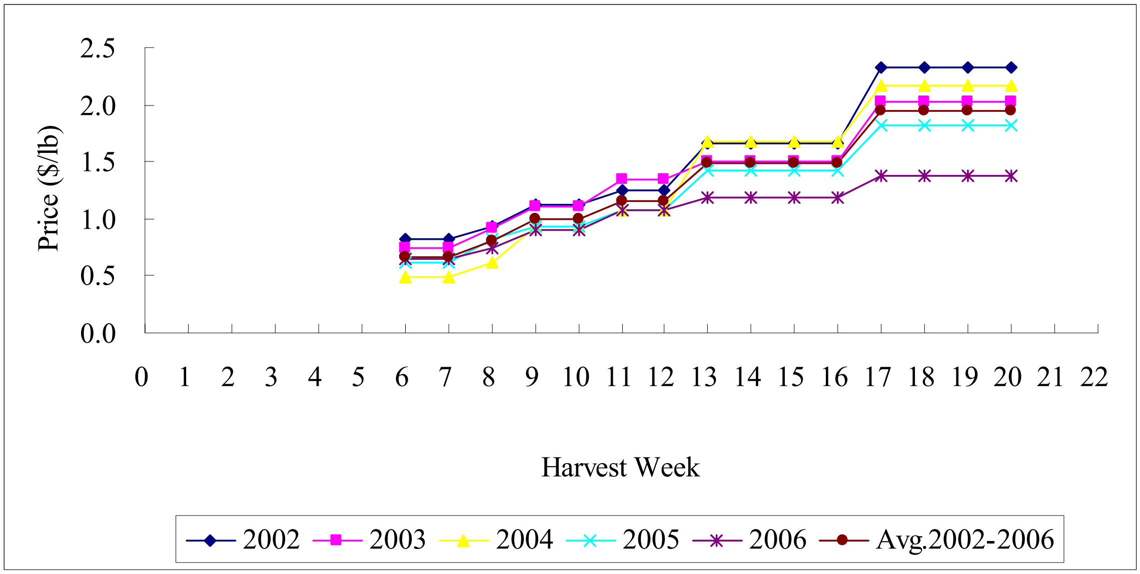

Figure 5.21 Price Relevant to Harvest Week for Tanks 1, 9 and 12 of GCRL

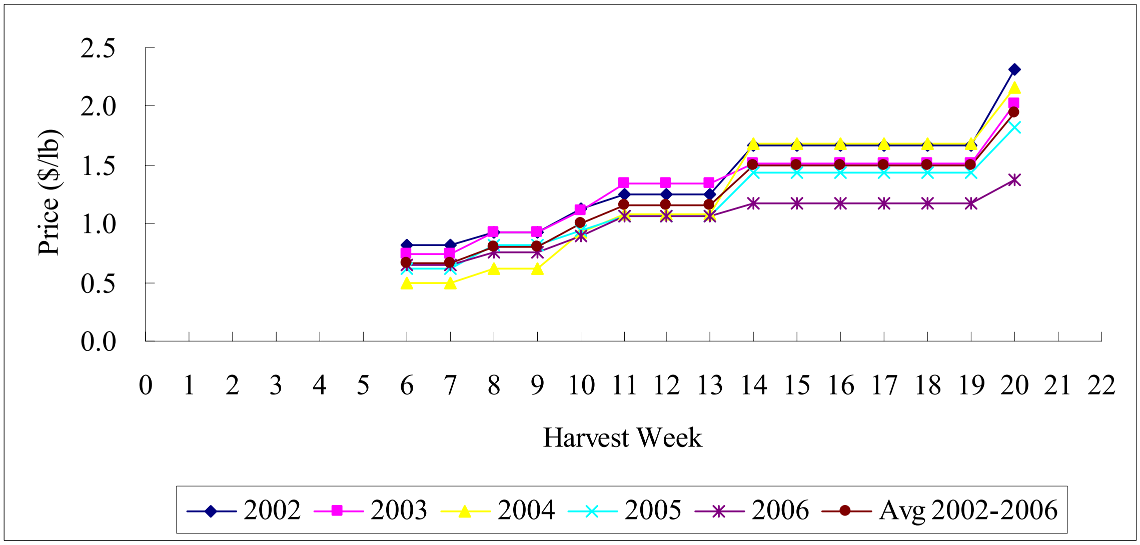

Figure 5.22 Price Relevant to Harvest Week for Tanks 2 and 11 of GCRL

In summary, the results chapter explained growth and feed regression outputs, analyzed the optimal harvesting strategy, and discussed the impact of price on the optimal solution and net revenue. These data analyses lead to the next chapter, the conclusions drawn from this research.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This chapter presents an overview of the entire study, followed by a summary of results. Then, conclusions are drawn and discussed. Finally, limitations of the study are discussed and suggestions are put forward to improve future research in this area of bioeconomic modeling of super-intensive recirculating shrimp production systems.

Overview

This thesis completed the development of a production-economic optimization step to be used in the economic evaluation of the super-intensive recirculating shrimp production system. The general goal of this study is to determine an optimal harvesting strategy to maximize net revenue for the super-intensive recirculating shrimp production system. This general goal was accomplished through the following specific objectives: 1) determining the optimal harvesting week, the optimal shrimp size to be harvested, and the optimal number of crops per year to maximize net revenue of the production system; 2) determining the impacts of survival rates on the optimal solution and the maximum net revenue of the production system; and 3) determining the impacts of historic shrimp prices from 2002 to 2006 by size categories on the optimal solution and the maximum net revenue of the production system. In order to accomplish these specific objectives, an inventory optimization model was developed to determine the optimal harvesting week, shrimp size, and number of crops per year to maximize net revenue on an annual basis for the production system; and to conduct a sensitivity analysis on net revenue by varying shrimp prices and survival rates. Data came from super-intensive recirculating shrimp production system experiments conducted at GCRL (MS), Waddell Mariculture Center (SC), and the Oceanic Institute (HI).

Shrimp researchers will be able to use the inventory optimization sub-model within the Hanson-Posadas bioeconomic model to guide their research activities toward areas providing greater net return or lower cost of production from these systems. Shrimp producers will be able to use the model in managing their operations to obtain higher net revenues. Investors and bankers will be able to use the model to better evaluate profit potential based on mold results and decide whether such projects are economically feasible to finance.

Previous studies have focused on super-intensive recirculating shrimp systems from the perspectives of biology, economics, and bioeconomic modeling. These studies covered technical feasibility and economic feasibility of the super-intensive recirculating shrimp production systems, shrimp price by size category, partial and final harvesting, stocking rate, growth and feed functions, and bioeconomic modeling of the production system. However, few studies have focused on optimizing the harvesting strategy to maximize annual net revenue of the production system.

Summary of Results

Shrimp growth and feed regression estimates were incorporated into the inventory model for each of seven groups: WMC-8, WMC-9, WMC-11, GCRL-1, 9, and 12, GCRL-2 and 11, OI-14, and OI-23. By running the inventory model for each of these seven groups, the optimal harvesting strategies were obtained to maximize annual net revenue of the super-intensive recirculating shrimp production system. These strategies are as follows: trials 8, 9, and 11 of WMC had the same optimal harvesting week of twelve; tanks 1, 9 and 12 of GCRL had an optimal harvesting week of seventeen; tanks 2 and 11 of GCRL had an optimal harvesting week of fourteen; OI-14 had the optimal harvesting week of twelve; and OI-23 had the optimal harvesting week of fourteen. Tables 6.1 and 6.2 present a summary of the optimal strategies and resulting maximum annual net revenue.

Table 6.1 Optimal Harvesting Strategies

Source	Stocking Rate ($Shrimp/m^3$)	Optimal Harvest Week (#)	Optimal # of Crops Per Year (#)	Optimal Harvesting Size (g)
OI-23	301	14	3.7	21.4
WMC-11	371	12	4.3	18.5
GCRL-1, 9, 12	401	17	3.1	18.9
GCRL-2, 11	401	14	3.7	15.5
WMC-8	420	12	4.3	18.6
WMC-9	450	12	4.3	18.6
OI-14	705	12	4.3	18.0

Table 6.2 Maximum Average Annual Net Revenue

Source	Maximum Average Annual Net Revenue with Varying Weekly Survival Rate (%)					
	99% ($/m3.Year)	98% ($/m3.Year)	97% ($/m3.Year)	96% ($/m3.Year)	95% ($/m3.Year)	94% ($/m3.Year)
OI-23	60.62	48.84	38.53	29.51	21.63	14.76
WMC-11	56.94	43.94	32.33	21.97	12.74	4.51
GCRL-1,9,12	42.58	29.33	18.11	8.6	0.52	-6.3
GCRL-2,11	22.17	13.45	5.79	-0.85	-6.72	-11.77
WMC-8	67.64	52.95	39.82	28.08	17.59	8.28
WMC-9	74.19	58.46	44.37	31.81	20.58	10.62
OI-14	63.87	45.53	29.14	14.50	1.45	-10.17

The optimal harvesting week occurred when the maximum value of the average weekly or annual net revenue was obtained. The relevant net revenue from one batch could not be the maximum value at the optimal harvesting week of the maximum annual net revenue. Weekly survival rates did not affect the optimal solution but did change the value of the objective function, i. e., the average weekly net revenue or the annual net revenue. The average weekly net revenue or annual net revenue was positively increased as the weekly survival rate increased.

Changing shrimp selling prices did not change the optimal harvesting strategy, but did change the value of the objective function. The average weekly net revenue or annual net revenue was positively increased as price increased. Also, price margins among shrimp size categories are crucial in the determination of whether to grow larger or smaller sized shrimp. As shrimp price is determined by size category, the degree of responsiveness of price to size changes determines whether shrimp should be grown to the current size category or harvested and sold at the previous size category. Within the same size category, shrimp should be harvested and sold at the end of the first week when shrimp grows to into this weight range.

Conclusions

The optimal harvesting strategy is determined by estimating the growth function and feed function using OI, WMC, and GCRL research data, including their stocking rate and survival rate (ratio of the research-level number of surviving shrimp divided by the number of shrimp initially stocked), and price received for each size category (Urner Barry), and associated input costs of production for items such as feed and shrimp PL stocked in the super-intensive recirculating production system.

Both growth and feed functions are determined by many complicated factors, such as water quality, temperature, climate, stocking rate, biomass, etc., but here focused were only two major growth contributing factors, feed and average weight over time. Based on the historic selling prices from 2002 to 2006, price and survival rate can affect the values of the maximum annual net revenue or average weekly net revenue, but they do not impact the optimal harvesting week choice.

Since the optimal harvest week to maximize the annual net revenue was obtained for GCRL, WMC, and OI, shrimp researchers can put the optimal harvest strategy output into the Hanson-Posadas bioeconomic model to attain commercial-scale results and determine economic feasibility projections for the operation and breakeven cost of producing shrimp in the system. Also, parameters needed by Hanson-Posadas model are as follows: 1) initial size (g), which can be obtained from the data; 2) ending size (g) at the optimal harvest week, which can be obtained from the optimization results of this study; 3) average growth rate (g per week), which can be obtained from the optimization results; 4) feed conversion ratio, which can be calculated as the quantity of feed fed per shrimp divided by the quantity of weight shrimp gains during the growth period; 5) survival rate (%), which can be calculated as quantity of shrimp survived at the end of growth period (optimal harvest week) divided by the quantity of shrimp stocked at the beginning; and 6) stocking rate (the quantity of shrimp per m^3), which can be obtained from the data. In addition, researchers can use the results and the inventory optimization model, as well as the Hanson-Posadas model to plan future research toward reducing production costs or improving biological parameters having the most positive impact on profitability of the super-intensive production system.

Shrimp producers can refer to the study results and use the inventory optimization model to more efficiently manage their operations. Shrimp producers using the super-intensive recirculating shrimp production systems from the Gulf of Mexico can refer to the results of GCRL; shrimp producers from South Carolina or nearby areas can refer to the results of the Waddell analysis; shrimp producers in tropical regions can refer to the results of the Oceanic Institute analysis. In addition, shrimp producers can harvest and sell their products at the end of first week when shrimp attain the highest price size range as the weekly survival rate remains high. Producers can apply the inventory model to adjust the optimal harvesting week as parameters change.

Limitations and Suggestions for Future Research

One of the limitations of this research was that production cost in the inventory model includes only feed cost and Post Larvae (PL) cost, both of which are variable costs. However, since the Hanson-Posadas bio-economic model can calculate all variable and fixed cost items of the super-intensive production system such as labor, management, maintenance, electricity, fuel, and equipment construction, the optimal harvesting strategy needs to be inserted into the Hanson-Posadas bioeconomic model to determine the commercial profitability of the super-intensive recirculating shrimp production system.

Data for different stocking rates is limited. Each trial of GCRL, Waddell, and the Oceanic Institute was based on a fixed stocking rate. The reason to optimize the shrimp stocking rate is that the optimal stocking rate can produce a higher return than sub-optimal stocking rates. However, the stocking rate and final produced weight is constrained by the biomass or carrying capacity of the production system. Thus, there should be an optimal stocking rate to maximize net revenue of the production system. To get the optimal stocking rate, each trial should be based on different stocking levels, keeping other factors fixed, though it is recognized that this would be an expensive research approach. Then the optimal stocking rate could be used in this research optimization approach to maximize annual net revenue for each trial. It is unknown whether the optimal stocking rate would change the optimal harvesting results obtained in this thesis.

Weekly survival needs to be recorded in future shrimp production experiments. Without accurate data, weekly survival rate is assumed to be fixed at 99% across all production weeks and then sensitivity analyses changing survival rates to 98%, 97%, 96%, 95%, and 94% is best that can be done. Survival rate and stocking rate are key factors in determining the profitability of the super-intensive production systems since these two factors determine the quantity of the output of the system. Thus, any research that can improve the weekly survival rate would improve the profitability of the system, which is dependent upon the biological technology of the system. It is understood that it is not presently known how to obtain accurate weekly survival rate estimates during a production experiment without harming the shrimp in the raceway. This is a basic research problem that would benefit researchers and producers and would be worth pursuing. If weekly survival data were obtained and regressed into a function with time, the results could be used in the inventory model to maximize net revenue. Accurate weekly survival data would most likely change the optimal harvesting strategy as each trial would likely have varying survival rates over time.

The results of this study were based on the 2002 to 2006 historic shrimp prices. During that time period, shrimp prices did not changed much. If both supply and demand for each size category of shrimp changed a lot, shrimp prices and price margins among shrimp size categories would change severely. This change could affect the optimized harvesting strategy results. Whether this change occurs in the future is unknown. Further studies on predicting shrimp price structure among the shrimp size categories, as well as optimization of the super-intensive production system, need to be conducted.

Partial harvesting optimization was not accomplished due to a lack of growth and feed data for partial harvesting within the super-intensive recirculating shrimp production system.

Growth data for trials 14 and 23 of the Oceanic Institute were limited. Based on the data, the growth and feed functions of both trials were linear. These linear growth and feed estimates did not fit well the concave growth and feed curves of empirical studies. Whether an optimal harvesting week occurs after the end of the growth period is unknown.

Further studies need to be conducted on the factors that determine the growth function and feed function to improve the estimation of net revenue for the super-intensive recirculating shrimp production systems. Experiments on partial harvesting and stocking rate need to be performed for the production system. Data should be recorded from quite a few observations so that more accurate regression estimates can be obtained. These will allow economists to improve their economic assessment of the optimal harvesting strategy for the super-intensive recirculating shrimp production system.

In summary, this conclusion chapter presented an overview of this thesis, a summary of results, a discussion of conclusions, and some limitations and suggestions to further develop the economic study in the area of bioeconomic modeling of super-intensive recirculating shrimp production systems.

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