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Shrimp aquaculture: an analysis of its evolution and organization; and the development of a shrimp growth model

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An Analysis Of Its Evolution And Organization; And The Development Of A Shrimp Growth Model

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Abstract

This paper examines the impetus for the development and subsequent rise of the shrimp aquaculture industry and continues by exploring a model that seeks to improve shrimp farmers' harvests by identifying specific variables affecting shrimp growth. Evidence reviewed from 1980 through today suggest that technological advancements, reduced prices, and increases in both the supply and demand for shrimp are positively associated with the industry's rapid ascent. The introduction of vertically integrated shrimp farms along with the ability for shrimp farmers to differentiate their products are also correlated with the industry's growth. Variables affecting shrimp growth were also studied to determine which ones significantly affected growth, with the objective being to enable farmers to more accurately manipulate those variables to achieve improved harvests. Data from a 1997 harvest was taken from one farm located in Belize and suggests four factors: two feed types, water temperature, and water salinity, all significantly affect shrimp growth. The week number the shrimp were in the pond and the physical pond the shrimp were grown in also significantly affect shrimp growth. The results for feed type, temperature, and salinity support previous studies that have looked at these variables and found them to significantly affect shrimp growth. The findings on week number and pond number open up a new area of study to improve shrimp growth performance.

Introduction

World-wide, the shrimp aquaculture industry produces over 600,000 metric tons of shrimp a year with a net value of approximately six billion dollars (Csavas, 1993). The industry has grown three hundred percent over the past two decades and exponentially since its inception in the late 1970's. Figure 1, depicts the growth in the industry that occurred over the 1980's alone.

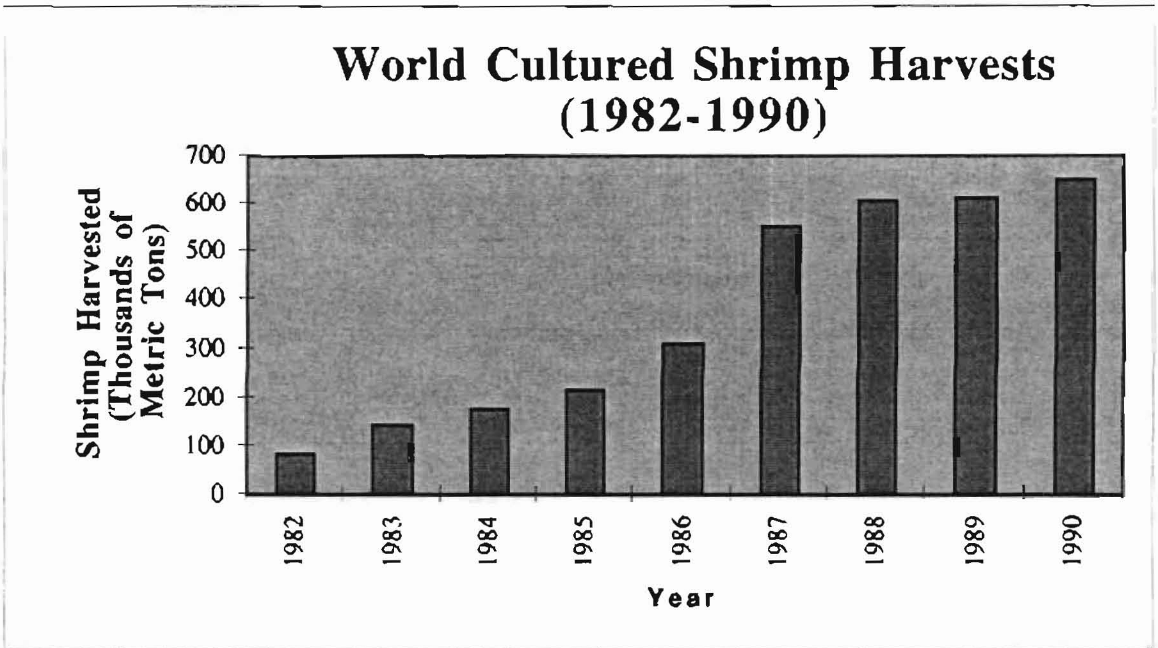

Figure 1. Growth in the Shrimp Aquaculture Industry During the 1980's.

The practice of shrimp aquaculture, also known as shrimp farming, has established itself as a formidable competitor to the wild-catch supply of shrimp which consists of trawlers that harvest shrimp in the oceans. Prior to 1980, shrimp aquaculture produced less than one percent of the total world-wide supply of shrimp with the wild catch supplying approximately one hundred percent. A revolution took place in the industry following 1980 and as of 1996, shrimp farming accounted for thirty percent of the world-wide supply of shrimp (Rosenberry, 1996).

This paper looks at the evolution of the shrimp industry and begins by taking an analytical approach to explain the causes for the industry's growth. Economic principles are used that focus on supply and demand changes along with technological advancements to explain the development. The paper continues by exploring the structure of the industry and the organization of the typical shrimp farm. Factors effecting supply and demand are then studied that explain what determines the world-wide demand for shrimp and how farmers react to such changes.

The paper proceeds by looking at the methods shrimp farmers pursue when differentiating their products, i.e. shrimp, and then takes an in-depth look as to how a

farmer can achieve differentiation by manipulating shrimp growth. A model is constructed that seeks to identify explanatory variables that significantly affect shrimp growth. The model also looks at weekly differences in total shrimp growth along with the differing roles shrimp ponds have on growth. From the model, farmers can better understand the influences that environmental variables, ponds, and time have on shrimp growth and as a result will be able to more accurately manipulate these grow-out parameters. By manipulating these parameters, farmers will be able to maximize the amount of weekly shrimp growth that transpires in their ponds. Greater weekly growth levels translate into increased final weights for shrimp at the time for harvest, the end result being larger total revenues and profits for the farm due to the greater harvest masses.

What is Shrimp Aquaculture

Shrimp aquaculture, or shrimp farming, can be paralleled with terrestrial farming because both involve raising a product in a specified area for future sale in a market. The practice of shrimp farming begins with stocking shrimp in ponds where they are left to grow and ends once they reach marketable sizes and are sold. Several steps, discussed below, are required for a successful outcome when raising shrimp.

The shrimp larvae used for stocking the ponds can be obtained in one of two ways. They are either raised in hatcheries and then transported to shrimp ponds for grow-out, or female shrimp bearing eggs are captured from the ocean and delivered to grow-out ponds. Once in the ponds, the shrimp are monitored daily by a pond manager whose job consists of manipulating pond conditions such as salinity, pH, and unionized ammonia concentrations. The manager also determines the amounts and times to feed the shrimp in an effort to maximize shrimp growth. Upon reaching marketable sizes, the shrimp are removed from the pond, processed, and are either exported to end consumers or stored for future delivery. The act of shrimp farming

contains many more intricacies but this brief introduction provides the reader with a general understanding as to what the practice entails.

History

The shrimp aquaculture industry has grown considerably over the past two decades and has become a major supplier of shrimp to the world market. This rapid ascent began in the early 1980's, but the practice of raising shrimp dates back centuries to Southeast Asia where locals raised shrimp that were trapped in tidal pools.. The locals kept the shrimp in the tidal pools until the shrimp reached a preferred size at which point they were harvested (Knud-Hansen, 1996). Practices such as these were isolated to coastal fishing towns and provided villagers with a source of food. No advancements were made in this practice until the 1930's when Motosaku Fujinaga, a graduate student at Tokyo University, later known as the "Father of Modern Shrimp Farming," successfully raised the species of shrimp *Penaus japonicus* (Knud-Hansen, 1996). The experiment was significant because it proved shrimp could be reproduced and grown to marketable sizes under controlled conditions outside of their natural habitat. At the time, there was no room in the market for a cultured shrimp sector because shrimping vessels, harvesting shrimp from the wild, were able to completely supply world demands.

In the 1980's shrimp aquaculture established itself in the market and Motosaku Fujinaga's ideas were put to use. Shrimp farms sprung up in many parts of Southeast Asia as well as parts of Latin America. These regions were selected because they provided optimal conditions for shrimp aquaculturists to grow shrimp. Their tropical climates, large tracts of cheap coastal lands, and inexpensive labor forces were ideal for setting up farms. To illustrate the growth that transpired in the industry between the 1970's and 1980's, 177,009 metric tons (mt) of shrimp were farmed with a dollar

value of $956,465,000 while in 1984 compared with only 17,000 mt while in 1975 (Rosenberry, 1995).

The shrimp aquaculture industry grew at a sizable rate over the course of the eighties as illustrated by Figure 1. The latter half of the eighties were plagued with uncontrolled expansion in the number of farms setup, and intensive methods used when farming. Environmental problems arose along with disease outbreaks that forced some operations to shut down. These effects were counteracted by continual technological advancements that improved the productivity of existing farms. Today, shrimp aquaculture provides approximately thirty percent of the worlds supply of shrimp (Rosenberry, 1997). The continued attainment of market share is projected by shrimp farmers as long as their management decisions are made efficiently, which include taking into consideration the externalities their farming methods create in the form of environmental problems. Two other factors that will also determine the success or failure of the industry are continued technological advancements and viability of the wild catch. The next section will analytically examine the development of the industry by explaining the factors that were responsible for shaping the industry.

Economics Behind The Evolution Of The Industry

The evolution of the shrimp aquaculture industry resulted from various changes in the supply and demand for shrimp along with external forces such as technological innovation and governmental programs. An outline linking each one of these factors can be constructed that logically explains the development of the industry. First, in the early 1980's technologies were developed in the methods shrimp farmers used to raise their shrimp, making it possible for farmers to economically compete with wild-caught shrimp harvesters. Farms arose in parts of Southeast Asia and Latin America and were viewed by venture capitalists as lucrative endeavors that could produce a

quick profit. The money venture capitalists put up, along with aid supplied by governments, provided the necessary capital to undertake the construction of more shrimp farms. The farms introduced more shrimp onto the market thereby deflating the prices for shrimp. As a result, consumer demand for shrimp increased and the increase was matched by more shrimp supplied by aquacultural means. The wild-caught harvester's didn't supply much if any of the increased demand for shrimp because their harvests leveled off after the mid 1980's due to over-fishing. Each of these steps will be broken down and analyzed further to develop a more complete understanding as to how shrimp farming was able to experience the growth it did. Figure 2, summarizes the above mentioned steps through a graphical depiction that includes an explanation.

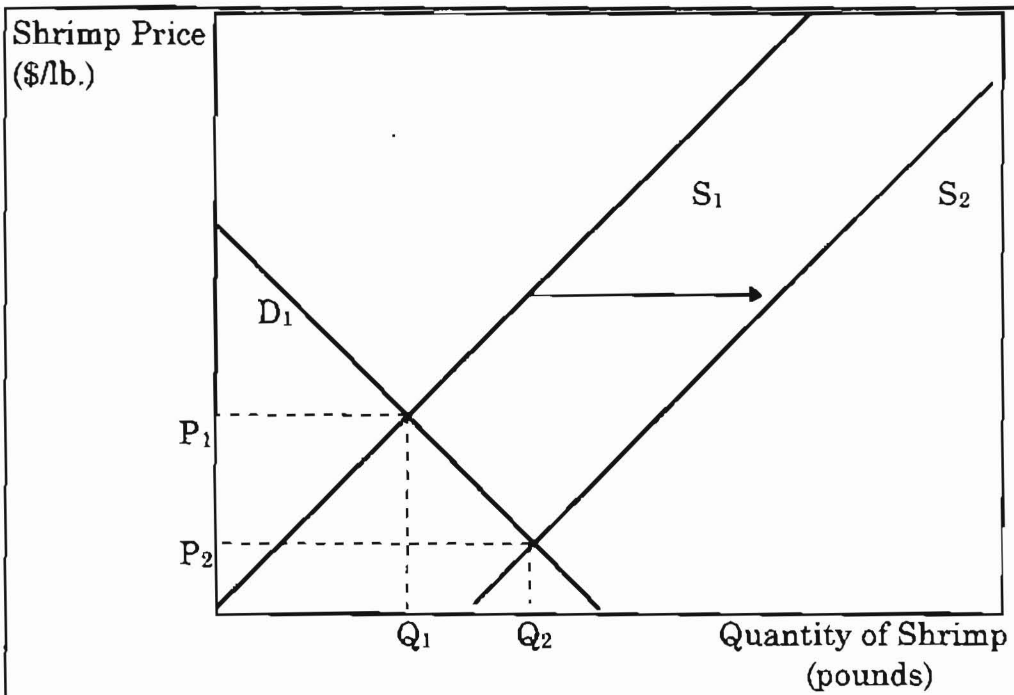

Figure 2. Evolution of Shrimp Aquaculture Industry.

(1) Prior to shrimp aquaculture the wild-catch supplied all the shrimp to the market (Q_1) and received price, P_1.
(2) Shrimp farming arose in the 1980's and as a result of technological advancements became a cheaper means to supply shrimp to the market.
(3) Shrimp farms were constructed world-wide and increased the supply of shrimp placed on the market (outward shrift of supply curve from S_1 to S_2, and increase in quantity from Q_1 to Q_2).
(4) The increased supply of shrimp decreased the price per pound of shrimp from P_1 to P_2.
(5) As a result of the decreased prices, the consumer demand for shrimp increased (downward movement along demand curve).
(6) Since the wild-catch supply of shrimp to the market leveled off during this transition, shrimp aquaculture met the majority of the increased demand by supplying quantity Q_1Q_2 to the market.

Technological Advancements: Feed

Technological advancements in shrimp farming came in many forms and arose in the early part of the eighties. Studies conducted at universities and government-sponsored studies were the major sources for these advancements. One of the most significant advancements was the development of high quality feeds. Prior to the 1980's it was known that the amount of protein a feed contained correlated positively with shrimp growth rates (Andrews, 1972), but no "designer" feeds had been created at the time. Then in the early 1980's high quality protein feeds were developed for

various aquacultural practices that coincidentally were well suited for shrimp (Horseman, 1994). These feeds increased the growth rates and survivability of shrimp and allowed farmers to achieve larger and faster harvests.

Technological Advancements: Water Circulation Systems

The improvement in feed quality created a new problem. Since farms placed increased amounts of shrimp into the ponds, waste accumulation in the form of fecal matter became an issue. The waste problem compromised the water quality and the question arose as to how it should be handled? Water circulation systems were developed as well as expensive pumping systems that farms began to invest in . These systems solved the poor water quality problem by pumping fresh, oxygenated water from nearby water sources, such as the ocean, into the shrimp ponds while removing highly turbid de-oxygenated water from the pond. The pumps also increased shrimp growth rates because improved water qualities were able to be attained within ponds.

Technological Advancements: Farming Methods

The development of pumps and improved feeds led to one of the most important advancements in shrimp farming, the introduction of new farming techniques. Before high quality feeds existed, the number of shrimp-larvae placed in a pond was limited to the supply of nutrients existing naturally within the pond. The shrimp only fed on the natural nutrients and farmers did not do more than harvest the pond once the shrimp reached marketable sizes. This method of farming was called extensive farming and was practiced world-wide prior to the development of the other farming techniques (Rosenberry, 1994). Extensive farming restricted the final amount of shrimp harvested because initial nutrient levels represented a limiting factor as to how many shrimp could be placed in the pond. Because of this limiting characteristic, increased revenues were possible through larger quantity harvests if supplemental feeds could be added to the pond to replace the lost nutrients shrimp consumed. High

quality protein feeds filled the role as the desired supplemental feeds and farmers were able to increase the amounts of their original stocking densities and thus their final harvests. As an off-shot to the high quality feeds, semi-intensive and intensive farming techniques were developed that enabled farmers to experience larger returns both in shrimp mass and pond revenues (Rosenberry, 1994). Water pumps were important in this transition because they allowed for the maintenance of high quality water in the ponds even when increased densities of shrimp were introduced.

Technological Advancements: Hatcheries

Another technological advancement that enabled shrimp farms to undertake in higher stocking densities was the development of shrimp hatcheries. Shrimp hatcheries provided farmers with consistent, large, and healthy supplies of shrimp larvae. Granjas Marinas San Bernardo, a Honduras based shrimp farm with hatchery capabilities, gives a sense of the magnitude shrimp hatcheries were capable of producing. This hatchery could supply up to one billion larvae for its farms in one year (Bennett, 1994).

The importance of hatcheries like San Bernardo's was that they were superior to the alternative means of attaining shrimp larvae which had previously involved catching larvae in the wild. The problem with capturing shrimp larvae in the wild was that the number of larvae caught fluctuated greatly depending on the time of year and climatic conditions. As a result, those shrimp farms relying on wild caught larvae were viewed as risky investments because a shortage in larvae could prevent the efficient operation of a farm. The introduction of shrimp hatcheries decreased the riskiness of investing in shrimp farms because the hatcheries were capable of producing steady stocks of larvae farmers could depend on. As a result farming operations could be run year round and the market supply of shrimp and their prices could be more stable.

Private Investment and the Cost of Farming

Once the technological advancements were implemented, shrimp farming established itself as a serious competitor in the world-wide market for shrimp. The competitiveness led investors, such as venture capitalists, to supply the necessary capital to construct shrimp ponds. These investors saw the ability to make a quick profit on their investments and jumped at the chance by constructing many ponds in Southeast Asia and Latin America. Although technological advancements required investors to undertake in more expensive capital investments, because of the need to purchase pumps and quality feeds, the costs were outweighed by the increased farmer revenues and reduced costs per pound of harvest. One study, conducted in Indonesia, showed the differences in costs between farmed shrimp and wild-caught shrimp to favor farmed ones (Laio, 1989). The results of the study found the cost to farm shrimp in 1989 to be $4.00/pound US and the cost to trawl for shrimp $4.10/pound US, a conclusion that suggested farming held a competitive advantage to trawling (Laio, 1989). The reason trawlers surpassed farmers as a more expensive means to produce shrimp can be understood when considering the major costs of each practice. To farmers, feed represented the main costs, whereas fuel costs constituted a large portion of trawler's costs. High fuel prices throughout the 1980's provided a valid explanation for the more expensive trawling costs for shrimp, while improvements in feed quality made farming more profitable. The price discrepancy between the two labor forces cites another area where shrimp farming holds an advantage. The majority of shrimp farming takes place in developing countries where labor is cheap, while the two largest trawling countries for shrimp, the US and Greenland, have high real wages for their labor force.

Governmental Assistance Into the Construction of Farms

Aside from venture capitalists, governments also played a pivotal role in developing the shrimp aquaculture industry during the 1980's. Governments in many

Southeast Asian and Latin American countries helped the industry grow by supplying aid to start-up farms in the form of tax breaks, loans, and capital. This aid had the added effect of luring foreign investment into the country to invest in the construction of the farms. An example of governmental assistance was the "transmigration plan," designed by the government of Indonesia with the objective to develop shrimp farming in the countries eastern region (Laio, 1989). The plan worked as follows: any company interested in building a shrimp farm in the eastern region was encouraged to do so by the government who provided the company with special low interest loans. While the farm was being constructed, the government, in the countries western region, taught workers the skills necessary for shrimp farming so that once the project was finished the workers could be transported to the eastern region to begin farming. The program was successful because it resulted in the construction of more farms in the country and trained workers in the art of shrimp farming.

The US government undertook a different course of action to help develop the shrimp aquaculture industry in the 1980's. Instead of providing incentives for constructing more shrimp farms in the US, which was not an ideal location for farming because of its climate, the government invested $22 million dollars into technological research (Rosenberry, 1994). The funding came in the form of feed, hatchery, and farming method studies, and was to be conducted at universities and other research facilities. As a result of the funding, the US became a world leader in supplying the technological know-how of farming to other countries.

Supply, Demand, and the Price of Shrimp

Technological advancements along with public and private funding have tremendously helped the shrimp farming industry evolve to its position in the current market. Along with those three characteristics, the supply, demand, and price for shrimp have also helped the farming industry in its development. The increasing amount of farmed shrimp supplied to the market over the past few years has played a

large role in the industry's successes. As previously mentioned, the wild-catch of shrimp leveled off following 1985 and has since produced approximately 2 million metric tons as Figure 3 represents (Csavas, 1993). With a constant supply of shrimp coming from the wild-catch and an increased amount coming from farming methods, the worlds total supply of shrimp rose during the 1980's and 1990's. The increase in supply has had an inverse effect on its price and as a result, prices have fallen during the eighties. The US price per pound of shrimp fell from $2.47 in 1979 to $2.07, in 1989 while in Japan the price per pound fell from 1,012 yen to 449 yen over the same period (Chauvin, 1993). The decrease in prices have brought about an increase in consumer demand and consumption of shrimp in the US, Japan, and Europe, the three major world markets for shrimp, as depicted by Figure 4. The increased demand for shrimp compounded by the leveling off of the wild-catch have provided shrimp aquaculture with the seed from which it has developed from.

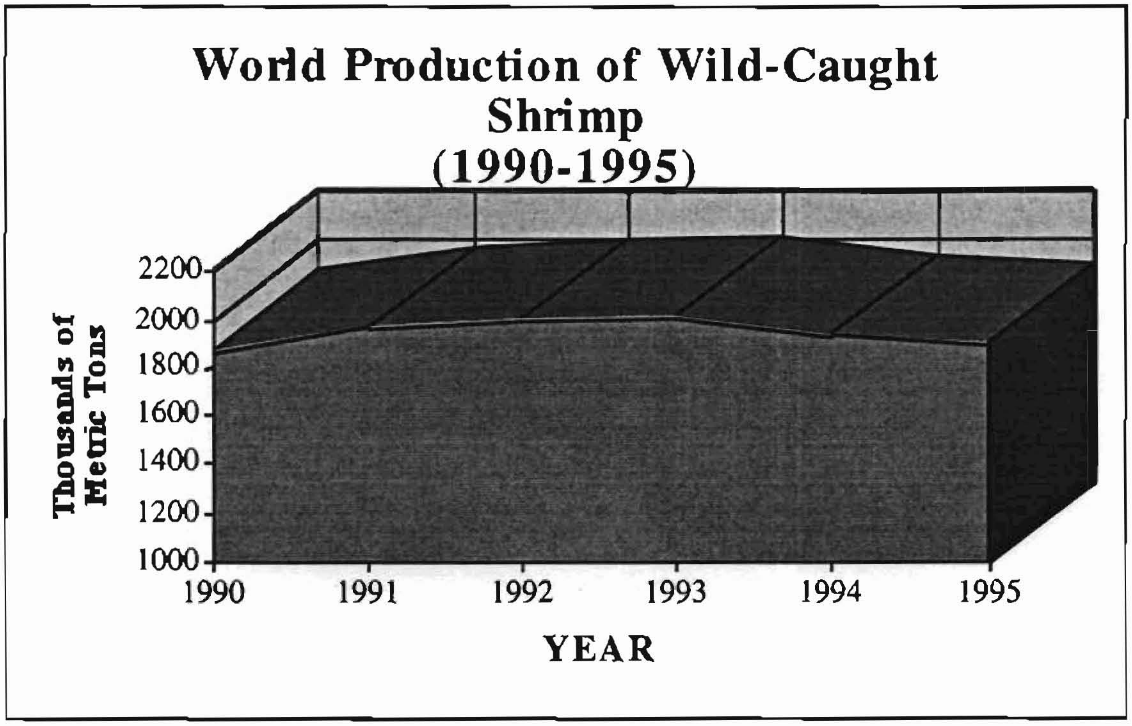

Figure 3. Leveling off of the Wild-Catch.

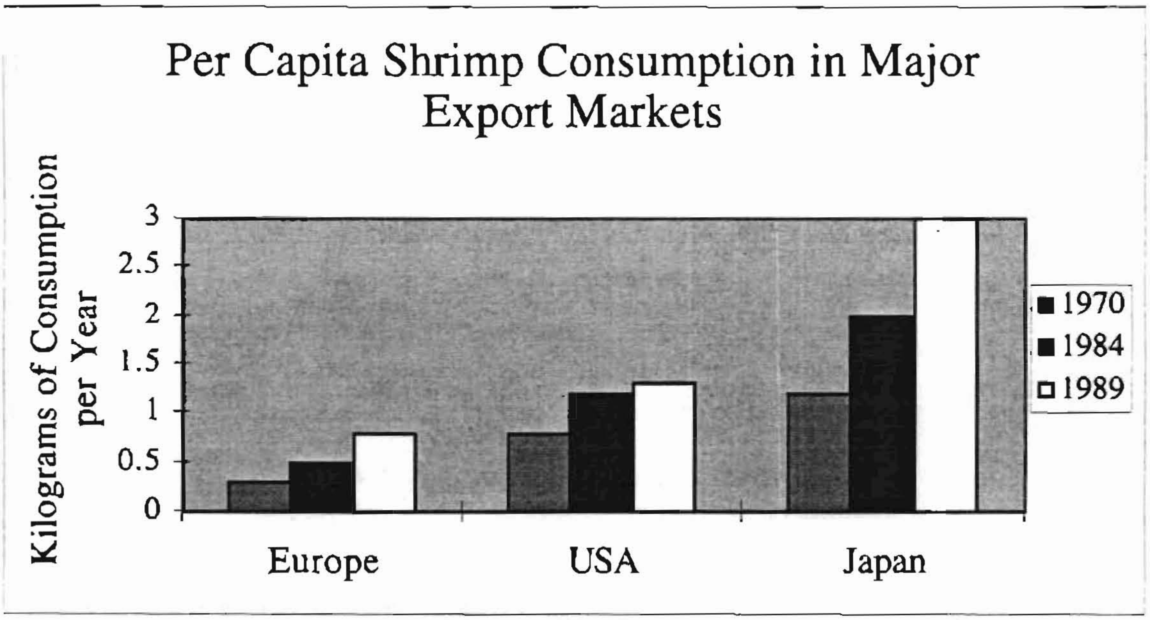

Figure 4. Increased Consumption of Shrimp in the Three Major World Markets.

Externalities Arising From Shrimp Aquaculture

The birth and ensuing growth of the shrimp aquaculture industry has been a successful undertaking with over 50,000 shrimp farms in operation today along with its employment both directly and indirectly of hundreds of thousands of workers (Rosenberry, 1996). The rapid development and growth seen in the industry has not been without its drawbacks. Many externalities have arisen that threaten the livelihoods of other coastal industries and shrimp farms alike. These externalities include, the devastation of aquatic ecosystems around the sites of shrimp farms, the introduction and spread of disease throughout ponds, and traces of antibiotic loads in shrimp placed on international markets.

One of the major requirements for shrimp farms is that they be located in the vicinity of a water source such as an ocean or a river. The preferred site for farms is along coasts where the ocean can provide an endless supply of water to circulate throughout the ponds and can act as a 'sewer' where pond effluent can be diluted once

it is pumped from the pond. The construction of ponds in these areas and the common practice of showing disregard towards environmental impacts have jeopardized the future of shrimp farming in some areas. An instance of the devastating effects shrimp aquaculture can incur was evidenced in the Philippines where the destruction of mangrove forests along coastal lands reduced the area of mangrove swamps from 448,000 hecta-acres (ha) in 1968 to 110,000 ha in 1989 (Laio, 1989).

The externalities that arise from such destruction of mangrove forests come in the form of severe impacts to the surrounding marine ecosystem. The severe impacts result because of the central role mangroves play in maintaining a healthy aquatic environment. When ponds are introduced to coastal environments containing mangrove forests, the mangroves act as filters and strain wastes, in the form of excessive nutrients. The wastes originate in the ponds and are released during the pumping process. When farms are built over the mangrove forests, and the forests are removed, inorganic nutrients released by the ponds are no longer captured and toxic conditions ensue in the water column. The toxicity comes in the form of anoxic water conditions and results in the death of shellfish and marine organisms. These adverse conditions have resulted in the crippling of local fisheries in some villages as well as severe hostility between shrimp farmers and fishermen.

Environmental externalities are not the only adverse impacts the development of the shrimp farming industry has created. Increased incidents of disease have arisen and resulted in the decline of harvest yields. Scientists have attributed disease outbreaks to the increased stocking densities many farmers have pursued as a means to maximize revenues. This problem was most severe in 1993, a period referred to as 'The Year Of The Disease.' During 1993, the annual world harvest from shrimp farms dropped for the first time in over a decade to 566,000 metric tons from its 1992 level of 713,000 metric tons (Rosenberry, 1994). The main culprit was Taura Syndrome Virus (TSV), a disease that broke-out across many of the world's farms and in Latin America caused an estimated $100 million of damages to farmers (Rosenberry, 1994).

Diseases were the cause for serious concern for many farmers, but another factor believed to be responsible for decreased annual harvests was pond mismanagement. One example of pond mismanagement occurred in Indonesia during the 1994 season where many farmers saw the collapse of their farms (Winarno, 1994). At first, the collapse was attributed to a disease outbreak but following a closer examination by scientists, it was concluded that the pond sediment had been severely deteriorated due to pond mismanagement. What had actually occurred was a protozoan outbreak that was responsible for the massive amounts of mortalities. Farm managers were not rotating the pond bottoms in between crops which resulted in their deterioration and the subsequent protozoan outbreak.

A final externality that arose while the shrimp aquaculture industry enjoyed its hay-day during the eighties and nineties dealt with the presence of antibiotics in shrimp. This problem arose because antibiotics were introduced in ponds to control for the spread of disease. The antibiotics were used, in excess by some farmers, to combat the spread of disease when an outbreak was detected. One publicized case where shrimp contained antibiotic residues involved Thai shrimp imported to Japan in 1991 (Csavas, 1993). Japanese authorities discovered traces of antibiotics in shrimp imported from Thailand and threatened to ban Thai shrimp if the problem was not taken care of immediately. In a matter of four months, antibiotic residues in Thai shrimp dropped from sixteen percent to zero percent as shown by Figure 5 (Csavas, 1993). The expedient manner in which the problem was rectified highlights the importance many countries with farming capabilities place on their relations with large consumers of their product. Since there are only three major markets for shrimp imports, a ban set-up by one could cripple the farming industry in a country. As a result, and as shown with Thailand, swift measures must be taken by the shrimping country to prevent the construction of such trade barriers.

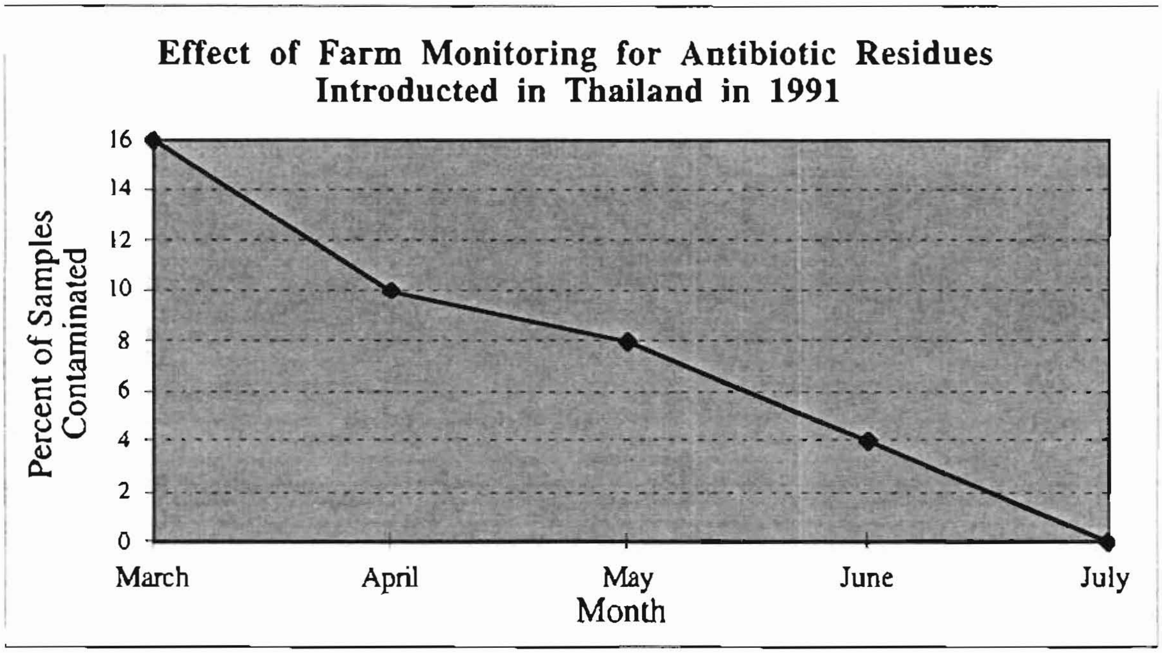

Figure 5. Percentages of Antibiotic Residues Found in Thai Shrimp Exported to Japan.

Market Structure

The shrimp aquaculture industry can be broken down into two hemispheres based on their production of shrimp and include the Eastern Hemisphere and the Western Hemisphere. The two hemispheres compete against each other for both inter- and intra- hemisphere shrimp markets. The Eastern Hemisphere has dominated the world markets, supplying approximately seventy-eight percent of cultured shrimp in 1996 (Rosenberry, 1997).

Shrimp farms in the Western Hemisphere are found mainly in Central America and the northern countries of South America, namely Ecuador which supplies over sixty-five percent of the cultured shrimp in the Western Hemisphere (Rosenberry, 1996). Islands in the Caribbean and a few states in the US also supply a small fraction of cultured shrimp. In total, 2,336 shrimp farms and 365 shrimp hatcheries

operated in the Western Hemisphere during 1996, combining for twenty-two percent of the world's production of farmed shrimp (Rosenberry, 1996). The predominant species of shrimp harvested here was *P. vannamei* otherwise known as the white shrimp. US consumers favored this species of shrimp which could be attested to by the fact that it was the most common shrimp served at restaurants. Europeans have acquired a taste for tropical shrimp and as a result have begun to import more shrimp from Latin American farmers. The expansion of the European market has provided Latin American farmers a growing market with which to supply their shrimp.

Although Ecuador contains the majority of the Eastern Hemispheres farms, Honduras possesses the worlds largest semi-intensive farming company in Granjas Marinas San Bernardo. This farm consists of five shrimp farms covering over 9,565 acres, two hatcheries, a processing plant, a technology development company, and a consulting company (Chamberlain, 1994). The processing plant has the potential to process 70,000 pounds of shrimp tails a day and the entire company employs over 1,311 workers directly and 812 indirectly (Rosenberry, 1996). Its capabilities are extensive and generalize that of many other Western Hemisphere farms in that on average they are more integrated than the Eastern Hemisphere's ponds.

The Eastern Hemisphere controls the majority of the world's shrimp farming industry with a seventy-eight percent stake in the market (Rosenberry, 1996). Throughout Southeast Asia, Australia, and India approximately 48,032 farms are in operation along with 4,638 hatcheries (Rosenberry, 1996). Countries in Southeast Asia such as Taiwan, Thailand, and Indonesia possess the largest portion of these farms and hatcheries. The islands and peninsulas that are characteristic of Southeast Asian countries provide potential farmers with plentiful sites for shrimp ponds because the locations are surrounded on most, if not all, sides by warm tropical waters.

The predominant species of shrimp harvested in the Eastern Hemisphere is *P. mondon,* also known as the giant tiger prawn (Rosenberry, 1996). The tiger prawn is

the most commonly raised shrimp in both the Eastern Hemisphere and the world. It accounts for sixty-four percent of the worlds farmed shrimp, almost all of which are farmed in the Eastern Hemisphere (Rosenberry, 1996). The tiger prawn possesses qualities that are desirable for shrimp farmers in their search for a species to raise. The shrimp is native to ocean waters in the South Pacific and provides an ample supply of larvae for farmers. They are the fastest growing shrimp species farmed, a quality that enables farms to perform more harvests in a year and thus provide larger quantities to the market. Finally, the taste of the tiger prawns is preferred by many people, a factor that has been shown by the increased number of exports to the US and Europe.

One of the distinguishing features of the Eastern Hemisphere's shrimp farming market is its size and the impact it has on local communities. In 1995 over 148,000 acres of land, converted to ponds, were utilized by farmers. During this period, the industry employed approximately 150,000 people with 97,000 of those directly employed by the industry (Rosenberry, 1995). The reason so many people were employed directly was because most of the farms were small scale operations where families oversaw and undertook in the work. There existed a few large cooperative organizations that contracted out with many small farmers to supply shrimp to the world-wide market. These companies, such as Aquastar based out of the Philippines, and BP Nutrition out of Thailand, were recognized world-wide and exported shrimp mainly to the three largest markets of the US, Japan, and Europe.

Organization of the Shrimp Farms

The structure and organization of shrimp farms have been dictated to a large degree by developments and improvements in technologies, such as those previously mentioned. The technological advancements have made it more efficient for farmers to internalize some of the production phases that were previously externalized.

Vertically integrated farms have arisen as a result of technology that make it possible for farms to contain phases for successful farming such as shrimp larvae hatcheries, processing plants, and international marketing divisions.

The advent of shrimp hatcheries have made it possible for farmers to attain continual supplies of shrimp larvae with which to stock their ponds. The advantages of hatcheries to farmers have been mentioned previously, but a summary will reinforce the reasoning as to why farmers would prefer to internalize this production stage. (1) Farmer's ponds do not have to lay idle, or un-stocked, when hatcheries are present because shrimp larvae can be supplied to ponds continually. (2) There are neither transaction costs nor transportation costs associated with hatcheries because farmers do not have to buy larvae from an outside supplier. (3) Farms can be setup in optimal areas for farming where the shrimp they harvest do not have to be non-native to the surrounding waters. The reasoning for this is that any shrimp can be raised at a hatchery. (4) Finally, farmers can avoid price fluctuations in the market for shrimp larvae because they are self-sufficient and can supply themselves with the larvae. These examples of advantages that hatcheries provide to farmers suggest that there are potential gains from internalizing the production of larvae.

Before shrimp aquaculture became a competitive industry during the 1980's most shrimp farms used processing plants that were used for either wild-caught shrimp or other seafood products. In neither case, were the plants located in close proximity to the shrimp ponds. Distant processing plants meant that following harvests, farmers had to transport their shrimp to the plants. The transport of shrimp involved transportation costs but more importantly caused a reduction in the quality of shrimp. Their quality decreases during the transportation process because shrimp meat deteriorates rapidly following death. Another problem of the wild-catch processing plants was that they were operated only during periods when the trawlers returned from a trip. As a result, there were long periods when the processing machinery lay idle. The continual harvests produced by shrimp farms throughout the

1980's and 1990's overcame these problems and created a more steady demand for processing capabilities. In turn, the downtime the processing plants experienced was reduced and the demand for on-site processing plants increased. A movement was seen in the industry where shrimp farms began to reorganize their structure to make on-site processing a part of the company. The transition to more on-site processing capabilities suggests that the benefits of improved quality and decreased transportation costs from the plants outweighed their costs of construction.

The addition of international marketing departments was another area where farms saw the ability to improve their efficiency of operation. Since the majority of shrimp farms arose in developing countries, the need to sell their products to developed and wealthier countries like the US and Japan became of paramount importance. The reason for this was that these developed countries offered higher prices for shrimp than what the farmers could receive in their traditionally poorer countries. Farming companies saw the need to establish marketing departments that enabled them to participate on the international market. Prior to these departments, farmers had to go through middlemen to sell their shrimp which involved transaction costs. But these costs could be avoided with marketing departments. Another important advantage the departments created was that they supplied farmers with more perfect information of market prices and demand for shrimp existing on the world market. As a result, farmers could make more efficient and practical decisions as to the most optimal means to operate their farms.

Hatcheries, processing plants, and international marketing departments are three developments that have shaped the organization of shrimp farming in both the Eastern and Western Hemispheres. Each hemisphere can be generalized as having its own form of organization, with large vertically integrated farms in the West and smaller farms run by large centralized companies in the East (Rosenberry, 1996). In the Western Hemisphere, the large vertically integrated companies are generally composed of a feed mill, a hatchery, growth ponds, processing plants, and a world-wide

marketing sector (Rosenberry, 1996). The advantages of having a hatchery, processing plant, and world-wide marketing sector were previously mentioned. But, the importance of having a feed mill on-site is that farmers are independent from external sources for supplying their feeds. Establishing independence is important because the price of feeds, like the price of shrimp larvae, fluctuate in the marketplace. Since feed makes up the largest portion of most farms operating costs, it is in the farmers interest to avoid these price fluctuations. Having feed mills at the site of the ponds eludes this problem and gives farmers a comparative advantage when selling their shrimp on the market.

Farming companies in the Eastern Hemisphere are different than those in the West. The majority of farms in the East are small scale intensive farms that join together in the thousands to form a cooperative organization under the sponsorship of a large organization, feed company, or government agency (Rosenberry, 1996). Aquastar and BP Nutrition, two previously mentioned companies, are both large cooperative organizations. These companies do not raise shrimp but devise contracts with small scale farmers who raise the shrimp. A typical contract states that the farmer is to supply the larger company with their harvests in return for feed, shrimp larvae, technical support, processing facilities, and marketing capabilities. The large company receives the revenues for the shrimp sales and takes their cut and distributes the remaining portion to the various farmers depending on their quantities harvested (Rosenberry, 1996). An example of the integration involved in one of these cooperative organizations is presented in Figure 6 (Csavas, 1993).

There are both advantages and disadvantages to each form of organization (referring to the differences between the structure of the farms in the East and West). The cooperative organizations found in the East have the advantage of diversifying their risk so that the organizations are not solely dependent on any one farm's shrimp production. This is an obvious advantage in the case where a disease outbreak or climatic condition adversely affects a farms production of shrimp. Another benefit of

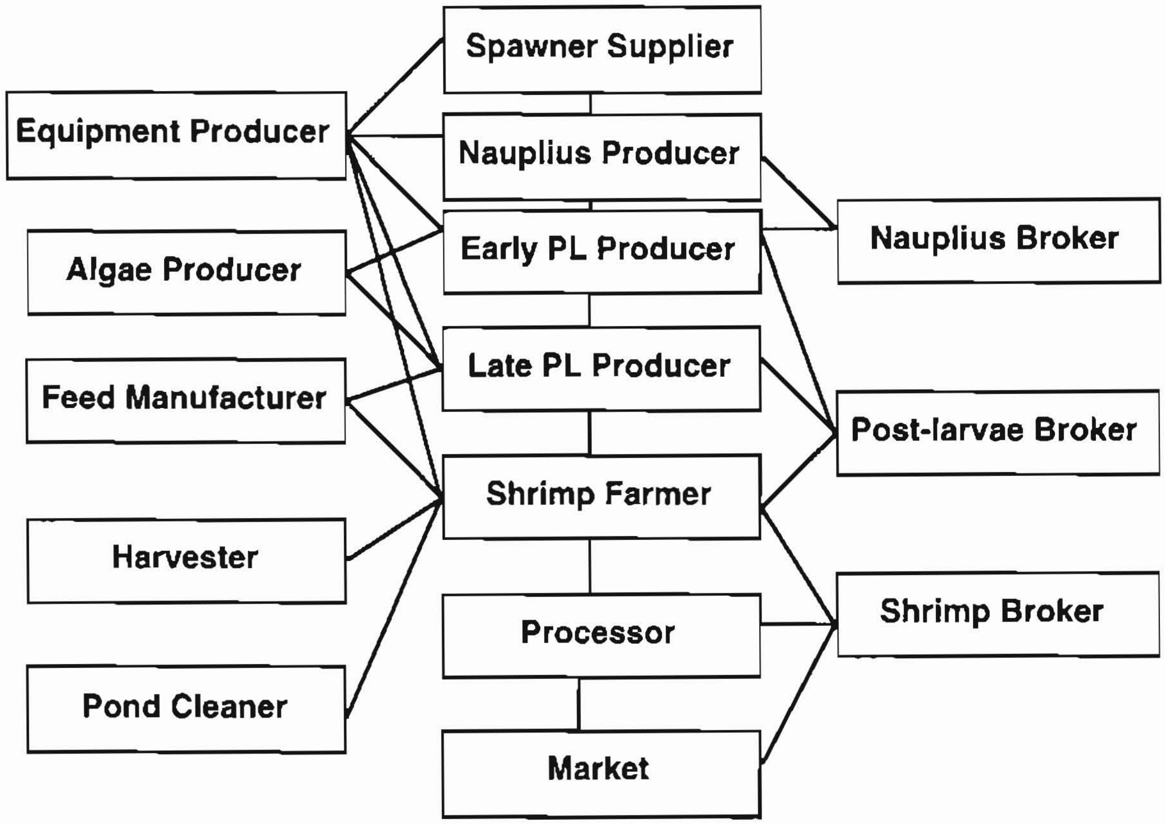

Figure 6. Pond Integration in a Southeast Asian Farm.

the East's organization is that they are capable of supplying more shrimp to the market than the West's because of the larger number of farms operated by each company. One problem that the East's organization presents is the principle-agent problem where the incentives of the owner and the pond manager are not perfectly aligned. Although the contacts between the two groups can dampen the agency problem, no contract is perfect and differences in incentives will inevitably result. One benefit that the West's organization has over the East's is that of decreased coordination costs. Since farms in the West are smaller and located in a centralized area their coordination costs are less. They do not have to coordinate the harvesting of shrimp in each pond to the same degree as farms in the East.

Factors Affecting Supply

Working from the previous knowledge discussed regarding the organization and properties of shrimp aquaculture, we can apply them to their affects on the supply of shrimp in the market. Technological advancements and disease outbreaks are the major sources mentioned that have the ability to affect supplies of shrimp. But, other factors exist that change the amount of shrimp placed on the market, cyclicality and seasonality, and they are the subject for the proceeding section.

The cyclical and seasonal nature of the shrimping industry plays a large role in determining the amount of shrimp that will be placed on the market. The cyclical aspect is best understood when viewing the harvesting practices of Ecuadorian farmers. They harvest their crops following lunar cycles and only harvest on new moons, or aguajes, during which time the levels of high and low tides are at there greatest ranges (Rosenberry, 1995). Since most shrimp ponds in Ecuador are located along the coast and are connected with the ocean, their water levels drop to the lowest levels during aguajes. The costs of draining the ponds for harvesting purposes are therefore minimized because the pumps, located in the ponds, only have to remove a minimal amount of water. The pumping of water into and out of ponds represents a cost to farmers and by lowering its costs, the farmers' operating costs are reduced. The practice of lunar harvesting is performed by most, if not all, Ecuadorian farmers and produces a surge in the amount of shrimp placed on the market. As a result of the jump in supplies of shrimp, market prices decrease. In order to combat some of these effects Ecuadorian farmers limit the amount of shrimp they place on the market after aguajes and store excess shrimp as inventories for later sales. Although lunar harvesting is mainly practiced in Ecuador, the size of its industry can impact world supplies of shrimp.

The effect of seasonality on the supply of farmed shrimp has the potential to impact the market more significantly than cyclicality because of its ability to affect

locations in a more universal manner. Seasonality refers to periodic variations which occur within a year, for example weather variations caused by El Niño, monsoons, or droughts. The changing seasons are another example of seasonality and have possibly the largest effect on farms and the quantities they produce at their harvests. In tropical areas, where most shrimp farms are located, the two seasons farmers face are the wet and dry seasons. The wet season produces a greater amount of rain which has the effect of cleansing the shrimp ponds and increasing the water quality. As a result, shrimp growth is usually faster during the wet season and the harvest is most often larger than during the dry season.

El Niño is an interesting climatic phenomenon that causes variations in the weather because it is currently affecting the globe. Shrimp aquaculture is one of many industries affected by El Niño because of its effects on the wild supply of shrimp larvae and conditions it creates within ponds. El Niño brings warm water currents to the Pacific Coast of the America's as well as heavy rainfalls (Begley, 1997). The warm water upwellings bring larger than normal amounts of shrimp larvae to the surface which are then caught by trawlers and sold as post-larvae to farms. More shrimp larvae are placed in ponds and farmers achieve greater harvests as a result. These abnormally large quantities of shrimp are then place onto the market. Heavy rainfalls in these areas also benefit farmers because they flush out any nutrient buildups in ponds and provide the ponds with fresh oxygenated water. Southeast Asia usually suffers misfortunes from El Niño because of severe droughts that occur in the region. The probability of seeing reduced supplies of shrimp larvae and increased incidents of contaminated ponds are thus increased here. As a result, shrimp ponds tend to perform poorly during El Niño years and the supply of farmed shrimp generated by Southeast Asian farmers is smaller.

Factors Affecting Demand

Now that the major variables affecting the supply of farmed shrimp are understood, an examination of factors impacting the demand for shrimp will be conducted. Factors affecting demand include substitutes, market prices, and health reports for shrimp. Each of these factors change the way consumers view shrimp, which affects their demand for shrimp. In addition to these factors, the ways in which farmers differentiate their products also impact the demand for shrimp, a topic that will be addressed in the next section.

The prices and quantities of substitutes for shrimp, offered on the market, play a role in determining the demand for shrimp. The primary substitute for shrimp is shrimp themselves along with other types of seafood (Platt, 1997). There are approximately six species of shrimp that are farmed: brown, white, pink, yellow, tiger prawns, and banana prawns, along with numerous other species caught in the wild that each possess different tastes. Customers develop their own tastes and preferences for particular types whether they be white or brown shrimp and therefore purchase the ones they prefer. When the market price for consumers' preferred shrimp increases due to a supply shortage, they look to other types of shrimp and/or other seafood's such as lobster or crab that may be priced lower. These alternatives are considered substitutes and their prices have the power to affect the demand a consumer places on a certain species of farmed shrimp. An example of this can be seen in the case of a restaurant who purchases a specific type of shrimp, most likely farmed, from a seafood broker. If the price for that product is too high relative to other types of shrimp the restaurant would want to rethink their decision to purchase the preferred product. They may opt to buy the cheaper shrimp in order to decrease their costs and increase profits. They will undertake in such practices as long as they believe their customers will not be able to notice the difference in taste of the cheaper shrimp.

Pork and poultry represent another substitute of seafood (in this section shrimp is grouped with seafood). The competition between these three products has favored pork and poultry because they are inexpensive to produce whereas the price for seafood is relatively high. The reason more seafood, like shrimp, is not sold at fast food joints, aside from Red Lobster, is because of its higher price. The tight competition that exists between places like Mac Donald's and Burger King make it even difficult for one of the two companies to sell a seafood meal because its price would be substantially greater than that for a hamburger or chicken meal. An exception to this rule is in New England where the demand for seafood is so great, especially during the summer months, that seafood entrees are sold at these places. For fast food restaurants, it is easier and more efficient to prepare the hamburger and chicken meals as opposed to seafood ones because of the ease of preparation. The simplicity of preparing meals aside from seafood raises another issue that explains why seafood has a difficult time competing for a niche in the fast food market. If the price of shrimp were to fall to a lower level than it is currently at, shrimp may be better able to compete with some of its substitutes in the market.

The strength of a country's currency directly impacts market prices for shrimp and represents another factor that affects the demand for shrimp. The effect of currency valuation was seen in Japan during the eighties when the yen was very strong relative to the dollar and other currencies. The strength of the yen meant it had a stronger purchasing power than other currencies and could buy more shrimp at the same price than previously. The growth in the strength of the yen gave Japanese importers leverage when biding for shrimp on the world market because a bid placed at a prior yen amount per pound could purchase more shrimp. The ability to purchase a greater quantity of shrimp with the same amount of yen had the effect of increasing Japanese demand for shrimp (assuming shrimp is a normal good).

One final factor that influences the demand for shrimp is their quality as perceived by consumers. Consumers are reluctant to eat foods that they believe may

endanger their health, and conversely are more apt to consume products that they assume to be healthy. Marketers and advertisers thrive off of this characteristic by way of commercials such as the Red Lobster ones, where fresh seafood is taken directly from the oceans, cooked to perfection, and then served hot to the customer. The seafood is pictured as tender and light when it is served, two qualities that people associate with healthy foods. Health reports have also fueled the perception of shrimp as a healthy food. One Kansas newspaper ran an article from a study stating that although shellfish, including shrimp, have high levels of cholesterol, the type of cholesterol they contain is healthier than the artery clogging type found in other foods (Mandelbaum-Schmid, 1995). The article proceeded to explain that shrimp are exceptionally low in saturated fats, a type of fat people try to avoid consuming because of its association with heart attacks. Studies like these increase consumer demand for shrimp because consumers develop tastes and preferences that associate shrimp with freshness and healthiness.

Differentiation of the Product

One of the greatest advantages shrimp farmers have over wild-caught shrimp is the ability to differentiate the product they supply to the market. This is a very important aspect of shrimp farming because it has secured farmers a spot in the growing market where demand for shrimp has steadily increased over the years. Differentiating the product, i.e. shrimp, can be achieved in a variety of ways most of which apply to methods over which the shrimp farmer has control. Shrimp trawlers, who catch shrimp in the open ocean, have a difficult if not impossible time differentiating their product because of their lack of control over the size and development of the shrimp they catch. The two forms of differentiation that are considered in the following section are the ability to differentiate shrimp based on their sizes and based on their species.

Differing the size of the shrimp at harvest represents an obvious advantage shrimp farmers have over the trawlers. Shrimp trawlers do not have the luxury to catch specific sizes of shrimp because of the variability involved with dropping a net into the ocean to catch shrimp. Conversely, farmers can monitor the sizes of shrimp they raise and once the shrimp reach a marketable size the farmers can harvest them. Farmers have the added ability to examine market conditions for certain sizes of shrimp while grow-out is underway which allows them to decide whether or not to harvest their ponds early or late. In this case, the farmers decisions are dependent upon what the market demand for shrimp is like for particular sizes. An example can better illustrate the advantages here but first an introduction to how shrimp are sized must be understood.

Shrimp can vary in sizes from small, smaller than a quarter, to large, up to one foot in length. The market has a universal methodology for differentiating these sizes that is based on the counts of shrimp per kilogram. An example would be a ten to twenty count where ten to twenty shrimp tails are equal to one kilogram (shrimp of this size would be considered jumbo). Marketers look at the demand for various sizes of shrimp and relay the information back to farms who adjust their harvests accordingly. If a shortage exists in the market for ten to twenty counts, which equates to higher prices, a marketer informs a farm about the shortage and the farm can act on the information. Farmers' method for acting involves letting shrimp remain in the ponds until they reach those sizes in high demand. A mutualistic outcome results where the farmer is able to attain greater revenues because of the higher market price they receive, while the market shortage is improved because of the increased supplies placed on it. Trawlers catching shrimp in the oceans have no such means to select for different sizes of shrimp since they place their nets in the waters blindly and capture whatever sized shrimp they happen to encounter.

Another method that shrimp farmers can pursue to differentiate their product is by selecting the type of shrimp they wish to raise. Once again, trawlers lack this

ability because they have no means to catch a specific species of shrimp. They can trawl in certain areas where they believe certain species of shrimp may be found, but they can not control what type of species ends up in their nets. The ability to differentiate the shrimp produced based on species is an important attribute for shrimp farmers because different countries desire different species of shrimp. The biggest markets in the world may demand white, brown, or pink shrimp and farmers can supply the type that is in greatest demand during any given period by stocking their ponds with the appropriate shrimp larvae.

Differentiating Shrimp Size by Manipulating Shrimp Growth

Now that an understanding has been attained as to the importance and advantages farmers can achieve by differentiating the size of shrimp prior to harvest, the focus of this paper turns to ways in which shrimp farmers can improve upon their ability to affect the growth of shrimp. The following section explains a model I developed and the model examines different explanatory variables and the amount of impact they have on shrimp growth. Six environmental variables, to explain shrimp growth, were considered that included three feed types, water temperature, water salinity, and the unionized concentration of ammonia in the water. Two other factors, weekly changes in the total growth of shrimp and the specific pond shrimp were raised in, were also explored to see how they impacted shrimp growth.

Farmers world-wide, manipulate the conditions in their ponds to attempt to increase shrimp growth rates but they lack the ability to quantitatively assess their actions. The model created in this study seeks to provide farmers with empirical evidence so that the farmers can more accurately affect shrimp growth amounts when manipulating the explanatory variables. In return, it could be possible for farmers to maximize their growth levels which would enable them to harvest larger shrimp at a quicker rate with the end result being greater revenues from shrimp sales.

Review of the Relevant Literature

The majority of published literature concerning environmental variables that effect shrimp growth have focused on the impact of one variable, such as water temperature, holding all others constant. This has been helpful in determining the individual affects a variable may have on shrimp growth, ceteris paribus, but does not provide a shrimp farmer with the variable's impact under realistic pond conditions. What a farmer ideally wants to know, in order to maximize the size of their shrimp come harvest time, is the effects on shrimp growth that each variable has when the others are not held constant. Testing of this sort should produce different results than when each variable is held constant. The reasoning behind this hypothesis is that environmental variables, such as water temperature and salinity, when free to change, effect the growth of some aquatic life (i.e. trout, catfish) differently than when one is held constant and the other is varying (Cuenco, 1985). Studies of this sort, that more accurately simulate real world conditions found in aquacultural ponds, have not been conducted for shrimp but have been performed on channel catfish (Cuenco, 1985).

Cuenco (1985) developed a dynamic model of fish bioenergetics and growth at the organismal level under controlled environments that provided a means for studying, evaluating, and improving the management of fishpond grow-out systems. The model identified five key variables; body size, temperature, dissolved oxygen, unionized ammonia and amount of food, and proceeded to determine their affects on the growth of channel catfish. The results showed that fish growth was more sensitive to changes in food consumption parameters than to metabolic parameters. Within each of these parameters temperature was shown to affect catfish growth more significantly than changes in parameters for fish body size, dissolved oxygen and unionized ammonia. The models Cuenco used took into account a series of behavioral and physiological processes that began with food intake and finished with the deposition of animal tissue to the sediment following fish death. The data and

scientific knowledge I had concerning these processes and their impact on shrimp growth was not as extensive as that found in Cuenco's study and thus prevented me from performing such complex modeling.

I took the environmental variables, cited as significantly impacting fish growth from Cuenco's experiment, and created my own shrimp growth model using those variables that I had data for. My model incorporated three out of the five environmental parameters contained in Cuenco's model, and included temperature, unionized ammonia, and amount of feed administered to the pond. Salinity was also introduced to my model because prior testing on shrimp had identified it as significantly effecting shrimp growth (Gunter and Hall, 1963).

I incorporated variables from Cuenco's (1985) catfish study into my model because no previous experiments have been performed on shrimp that use a dynamic growth model. Experiments have been performed that identify individual environmental variables effecting the growth of shrimp, ceteris paribus, and they observed the impacts of temperature, salinity, unionized ammonia, and feed type on growth (Cruz-Suarez and Ricque-Marie, 1994, Andrews and Sick, 1972, Waybam, 1991, Menz and Blake, 1980 and Colt and Techobanglous, 1978). The objective of these studies has been to determine the optimal levels of these variables so that shrimp growth can be maximized. They have all accomplished this by holding other variables constant while conducting the tests. As previously mentioned, experiments of this sort do not provide the exact information aquaculturists are interested in because realistic pond conditions are not simulated. My model seeks to provide information for realistic pond conditions by using data from actual shrimp ponds, where environmental parameters are subject to change. From my model, those environmental variables, significantly affecting the growth of shrimp, will be determined.

Feeds can be categorized based on their percentage of protein. Feeds containing larger protein percentages are priced higher and are considered to be of better quality

than feeds consisting of lower levels of protein. These high quality feeds are important since shrimp growth depends on the nutritional quality of the protein feeds (Cruz-Suarez and Ricqu-Marie, 1994). Therefore, when the farm manager determines how they are to feed their ponds they must weigh the costs of higher priced protein feeds against the benefits of the faster growth rates the feeds produce. To date no formulation promoting the optimal growth of shrimp has been developed but studies have been conducted that look at the relationship between different protein levels and their impact on shrimp growth.

Andrews and Sick (1972) performed some of the first experiments of protein feeds and the influence feeds have on the growth of penaid shrimp. Some of their results surprised scientists because shrimp fed diets of thirty-two percent protein showed significantly larger gains in growth per day than those fed either forty percent or fifty-two percent protein feeds. Another group of tests Andrews and Sick conducted produced results that were supported by the existing theory that, a positive correlation should be found between the amount of protein in feeds and shrimp growth. Shrimp fed diets of fourteen percent and twenty-three percent protein had significantly smaller growth levels than shrimp fed the thirty-two percent protein diets. From this group of experiments it was concluded that the thirty-two percent protein feeds produced the optimal amount of growth in penaid shrimp.

Of all the environmental factors affecting a pond, temperature was considered to have the greatest impact on shrimp growth. In F.E.J. Fry's categorization of environmental impacts on aquatic life, temperature was considered the principal controlling factor dominating the physiology and behavior of aquatic organisms (Neill and Bryan, 1991). Many texts have found that optimal temperatures for shrimp growth are between twenty-five and thirty-two degrees Celsius. A narrower range was suggested using the "Galveston method" and states optimal temperatures should be between twenty-eight and thirty degrees Celsius. Scientists agree that

temperatures greater than thirty or thirty-two degrees Celsius place an added burden of stress on shrimp that results in reduced growth levels (McVey, 1983).

A study by Wayban (1995) dealt with water temperature and its affect on the growth of white shrimp. The experiment raised four different sizes of white shrimp in three different water temperatures and compared their growth rates. The results concluded that temperature significantly effected the growth rates for all sizes of shrimp. When the temperature was below twenty-three degrees Celsius the shrimp experienced reduced growth and feeding rates. Small and medium sized shrimp (greater than ten grams) grew the fastest and to their largest sizes, in water temperatures that were above thirty degrees Celsius while the largest shrimp (greater than fifteen grams) grew fastest in twenty-seven degree water. The study demonstrated that white shrimp were sensitive to small temperature changes. The findings also showed the optimal temperature for shrimp growth to be between twenty-seven and thirty degrees Celsius, with the results depending on the size of the shrimp. In my model the natural logarithm was taken for both shrimp growth and temperature because neither of these terms grew in a linear fashion. The affect that a one degree change in temperature has on shrimp growth depends on where the temperature change occurs. By taking the natural double logarithm for both temperature and shrimp growth I am able to capture this effect because I linearize the curves for temperature and shrimp growth.

Salinity was the next environmental variable considered in my model. Little attention have been devoted by scientists as to the impacts of salinity on the growth of shrimp when raised under aquacultural conditions. Minimal information has been gathered regarding salinity's effect on the growth of white shrimp and giant tiger prawns, the two most common species of shrimp harvested. Scientists know that in the wild, the species of white shrimp, *P. vannamei*, can survive in salinity's ranging from one part per thousand (ppt) to extremely saline waters of forty parts per thousand and higher (Menz and Blake, 1980). This can be compared with other

species of white shrimp such as *P. setiferus*, *P. aztecus*, and *P. duorarum* all of which have been found in salinity's ranging from one part per thousand to over forty-seven parts per thousand (Gunter and Hall, 1963). From these studies it can be concluded that shrimp are tolerant and can survive in an extreme range of salinity's, but what aquaculturists are most interested in is the optimal salinity that will maximize shrimp growth.

One experiment performed by Boyd (1989) found that salinity's between fifteen to twenty-five parts per thousand were "considered ideal" for the raising of white shrimp. Another more extensive experiment was conducted by Bray (1994) and compared the growth of *P. vannamei* at salinity's ranging from five to forty-nine parts per thousand under pond simulated conditions. The results concluded that these shrimp showed significantly greater weight gains when raised at salinity's of five and fifteen parts per thousand compared to those grown under higher salinity conditions of twenty-five, thirty-five and forty-nine parts per thousand. A final notable study relating to salinity was performed by Huang (1983) and showed decreased growth levels in *P. vannamei* post larvae when raised under high levels of salinity. As with temperature, my model takes the natural logarithm of salinity since previous tests suggest that there is a non-linear relationship between shrimp growth and the salinity of the water.

Very little is known about the effect of unionized ammonia on the growth and metabolic processes of marine organisms (Cuenco, 1985). Colt and Techobanglous (1978) experimented with channel catfish and concluded that increasing concentrations of ammonia decreased catfish growth in a linear fashion. Although studies relating ammonia to growth are uncommon, many others have been conducted on ammonia's toxicity (Colt and Armstrong, 1981). These have proven the hypothesis that ammonia is toxic to marine organisms and adversely effects their metabolic processes. Thus it would be assumed, as Colt and Techobanglous (1978) found, that ammonia has a negative impact on growth.

Data and Methods

Sources. The data for this study was collected from NOVA Companies Belize Limited, a shrimp farm based out of Ladyville, Belize. The data set includes recordings from sixteen ponds of which each pond has between twenty and thirty-one weeks worth of observations for variables existing in each pond. The farm contains twenty-seven shrimp ponds in total that cover over 575 acres. The ponds are located on a one-half mile strip along the Caribbean Sea with 3,000 feet of mangrove forest separating the ponds from the ocean. On average, the ponds are twenty-five acres in size and constructed in such a way as to allow sea water to enter and fill them. The uniformity in water quality and the similar climactic conditions effecting all ponds due to their relative proximity enabled me to set up a cross-sectional function in my model.

Variables. Ponds at the NOVA farms are stocked and harvested (which collectively are known as a cycle) semi-annually. The first cycle starts in February and ends in May-June while the second harvest commences in August and is harvested in November-January. The data for the model are taken from the first harvest of the 1997 year (1997A). The length of the harvests for individual ponds varied between twenty weeks (pond nineteen) and thirty-one weeks (pond ten).

The shrimp larvae that NOVA used for stocking their ponds came from two outside suppliers. The supplies provided them with the two species of shrimp *P. vannamei* and *P. stylirostris*. These larvae, when first placed into the ponds for grow-out, varied from seven to ten centimeters in length. The initial size was not a factor in my model, only the measured weight of the shrimp following the first week's recording. The data-set also did not differentiate between the suppliers of the larvae and considered them of equal quality. Prior to the introduction of the shrimp larvae, each pond had undergone similar preparations. They were drained following the second harvest in 1996, dried to oxidize the organic components left from the previous

culture, and disinfected through the use of chemicals to quicken the rate of oxidation, in preparation for the first harvest in 1997. Once the ponds were ready for the first harvest in 1997 they were filled with ocean water that possessed similar chemical and physical qualities such as pH, salinity, and temperature. Shrimp larvae were then dumped into the ponds and left to grow until they reached marketable sizes. The larvae were contained within the pond for the entire grow-out period by earth and manmade barriers that separated each of the sixteen ponds from each other and the ocean.

While in the growth ponds, the shrimp were fed a specialized diet twice a day that was supplied by one of eleven different feed suppliers. The data-set grouped the feeds into three different qualities, forty percent, thirty-five percent, and thirty percent based on their respective protein percentages. There was no difference in quality between one supplier's forty percent protein feed and another supplier's forty percent protein feed and the data-set grouped the two as the same. Data were recorded that identified the amount and type of feed administered to the pond each day. These recordings were taken three times a day and corresponded to the three meals shrimp were fed a day. Feed was entered into my data set as the total amount of feed administered to the pond during the week. Feed type was recorded based on the feed type that was added to the pond in the largest quantity over the week. If week three's feed consisted of eighty pounds of thirty-five percent protein, and twenty pounds of thirty percent protein then the data set entry would state: thirty-five percent protein feed was placed into the pond during week three.

Sixteen out of the twenty-seven ponds NOVA owns were operated during their 1997A harvest. In each of the sixteen ponds, records were taken every day starting with the initial stocking date and finishing with the day the ponds were harvested. The recordings consisted of forty-nine different variables and included a variety of measurements such as water turbidity, color of the algae in the pond water, unionized ammonia concentrations, and other pond characteristics. Some records were taken

once a day, others were taken two to three times a day, and some others were measured on a weekly basis. Of the forty-nine variables recorded, this study examines five that were collected in the 1997A harvest. The five variables included: (1) shrimp growth levels, measured on a weekly basis in grams per week, (2) quantity and type of feed administered to the pond, the quantity of feed was measured in pounds per week and was calculated by summing the total amount of feed dumped into the pond over the week. The type of feed was recorded as either forty percent, thirty-five percent, or thirty percent depending on the predominate feed administered to the pond that week; (3) water temperature, taken in degrees Celsius twice a day in both the morning and afternoon and averaged to solve for the weekly temperature reading, (4) salinity, measured once a day on a scale of zero to thirty-two parts per thousand (where zero parts per thousand was equal to fresh water and thirty-two parts per thousand was pure ocean water) The daily recordings were averaged to determine the weekly salinity recording; and (5) unionized ammonia concentrations, measured daily in parts per thousand. The daily recordings were averaged to determine the weekly ammonia recording. It is important to note that farmers' estimates were used for growth rates of shrimp for the first four to five weeks of each cycle because the shrimp were too small in size to measure accurately.

Model Specification

I developed a pooled cross-sectional/time-series multi-variable regression model took the natural logarithm of the dependent variable along with three of the six independent variables. I performed several iterations that explored different functional forms and combinations of explanatory variables to come up with a model that best explains the weekly level of shrimp growth. During the developmental process of the model, I ran regressions for different models such as log-linear and linear-log models, but none of them produced the coefficients that I was searching for

aside from the model I actually used. I also ran tests for the six different environmental variables that included the use of quadratic terms, but the coefficients I obtained from these tests were not supportive of the previous literature.

Temperature, unionized ammonia, and type of feed were identified by Cuenco (1985) as significantly impacting fish growth and provided me with the reasoning for incorporating them into my model. Salinity was also added to the model since prior testing had concluded that it significantly effected shrimp growth (Gunter and Hall, 1963). I introduced two new variables to my model that separate it apart from prior studies. The two new variables include cross-sectional and time-series dummy variables for both ponds and weeks. Pond dummies were added to measure the differing effects that placing the shrimp into separate ponds had on the overall growth of the shrimp. Week dummies were introduced to determine the impact that each week of the harvest had on the growth of shrimp.

The goal of my model was to identify independent variables that significantly impact shrimp growth. This would provide farmers with an accurate understanding of which variables effect shrimp growth when subject to conditions that do not control for specific parameters. Another objective of the model was to provide farm managers with numeric values about the impact their actions had on the efficiency of pond growth. The proper knowledge regarding numeric values would allow farmers to more accurately manipulate pond conditions so that they could maximize the growth level of shrimp during the harvest. I also wanted to test to see if there were sizable differences in growth when shrimp were raised in different ponds. Testing of this sort would enable farmers to favor those ponds that produced better growth results and stock them with greater amounts of shrimp. Finally, I wanted to measure the magnitude of the effect that the week number had on the growth of shrimp. Having this information could give farmers a better understanding of what the shrimp growth curve looks like so that they could select the optimal week to harvest their crops in.

The empirical model consists of one equation. It models the effects of environmental variables, pond dummy variables, and weekly dummy variables on the level of shrimp growth. The shrimp growth model is represented by:

$$\text{Ln } y_{ix} = \beta_0 + \beta_1 f40_{ix} + \beta_2 f35_{ix} + \beta_3 f30_{ix} + \beta_4 \log t_{ix} + \beta_5 \log s_{ix} + \beta_6 \log a_{ix} + \sum_{i=1}^{27} \beta_{(i+6)} {}^{*} D_i + \sum_{x=2,19,8,7,9,13,4,3,15,1,5,6,11,14,10}^{15} \beta_x {}^{*} P_x + \varepsilon$$

where:

y_{ix}= the natural logarithm of total mass of an average shrimp in pond x during week *i*,

$f40_{ix}$= the amount of forty percent protein feed administered to pond x during week *i*,

$f35_{ix}$= the amount of thirty-five percent protein feed administered to pond x during week *i*,

$f30_{ix}$= the amount of thirty percent protein feed administered to pond x during week *i*,

t_{ix}= the natural logarithm of the average water temperature for pond x during week *i*,

s_{ix}= the natural logarithm of salinity for pond x during week *i*,

a_{ix}= the natural logarithm of unionized ammonia concentration for pond x during week *i*,

D_i= dummy for week *i*, its value is 1 during week *i* and 0 during all other weeks

P_x= dummy for pond *x*, its value is 1 for pond *x* and 0 for all other ponds.

In this model, the natural logarithm (from now on referred to as the log) is taken of the dependent variable (shrimp growth per week) because shrimp do not grow in a linear fashion. Shrimp growth during the juvenile stage increases slowly and then quickly during the maturation period and then increases at a decreasing rate upon reaching adulthood. Figure 7 represents these characteristics in shrimp growth for pond number 2:

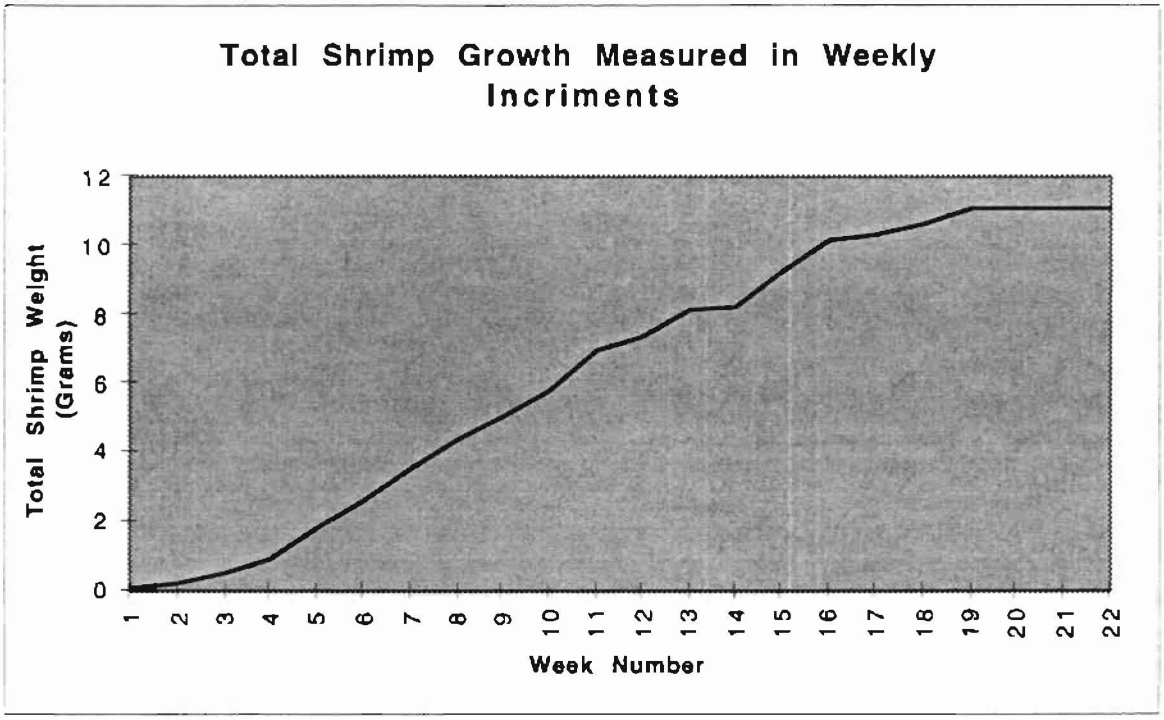

Figure 7. Total Weekly Growth Levels for the Average Shrimp in Pond 2.

The first three terms in the equation, f40, f35, f30, are the amounts of forty, thirty-five, and thirty percent protein feeds administered to pond x during week i. The terms could not be logged because although they are not true dummy variables, they are also not true continuous variables, and have a lot of zeros in their recordings. If the coefficients for feed are positive, which is to be expected, it means that weekly shrimp growth increases when increased amounts of feeds are added to the ponds during the week. Conversely, if their coefficients are all negative then an increase in

any of the feed variables results in a decrease in weekly shrimp growth. The marginal influence for these variables relative to shrimp growth is proportional to the level of shrimp growth. In other words, the influence on shrimp growth that a forty percent protein feed has is proportional to the size of the shrimp during the given week. The magnitude of the effect (the coefficient for the forty percent feed) is equal to the relative or proportional rate of change in the amount of shrimp growth from one week to the next for a one pound change in the amount of forty percent feed added to the pond.

The fourth, fifth, and sixth variables for temperature, salinity, and ammonia are logged because their individual effects on shrimp growth are nonlinear and nonaddative. For these independent variables, their marginal effect on shrimp growth varies directly with the level of shrimp growth and inversely with the value of that variable. In other words, the effect on shrimp growth of a one degree Celsius change in water temperature depends on where the change in temperature occurs, and whether it's at a high temperature or a low temperature. The same definition applies to salinity and the concentration of unionized ammonia. The coefficient for temperature is interpreted as: a one percent change in the average weekly temperature, ceteris paribus, changes the level of shrimp growth a percentage equal to that of the coefficient. Once again this holds true for both salinity and unionized ammonia. The expected coefficients for each of these variables varies. The expected coefficient for temperature should be positive because although the average temperature of the ponds was 29.3 degrees Celsius, a greater number of samples were found below the average at temperatures ranging from twenty-eight and twenty-nine degrees Celsius, which are lower than the optimal temperature specified in the previous literature, thirty degrees Celsius (Waybam, 1995). Conversely, the expected coefficients for salinity and unionized ammonia should both be negative. Since unionized ammonia is toxic to shrimp its expected effect on shrimp growth would be negative. Salinity's coefficient should be negative because the average salinity in the

ponds was twenty-five parts per thousand, which is greater than the amount of salinity cited in the literature as optimally effecting shrimp growth of five to fifteen parts per thousand (Huang, 1983).

The dummy variables for week, variables seven through thirty-three, consist of weeks two through twenty-seven. By using the dummy variables I am allowing for the most flexible form of nonlinearity. Week one, termed the reference or comparison week, is dropped to prevent multicollinearity from arising. The shrimp growth that occurs in the other weeks are all compared to the reference week. Therefore, if the coefficient for week X is positive relative to week one, a greater amount of shrimp growth occurred during week X. The main reason week one is dropped is because it is a week that each pond has an entry for. Weeks twenty-three through twenty-seven do not have recordings for every pond since some ponds are harvested earlier than others. The effect that any of the week dummy variables has on the growth of shrimp is equal to the value of their coefficient when the variable is present or the pond is left to grow for that amount of weeks. The expected sign for the coefficients for week should be positive because relatively little grow occurs during week one as compared to the other weeks. The numerical value of the coefficients should increase in size as the weeks progress and begin to decrease in size but remain positive as the final week nears.

The pond dummy variables, thirty-four through forty-eight, consist of all the different ponds that are raising shrimp during the first crop cycle of 1997. Pond twelve is dropped from the pond dummies included in the data set to prevent multicollinearity from arising, and similar to week one it is coined the reference pond. Hence, all the other ponds are compared to pond twelve. There was no particular reasoning behind dropping pond twelve and it was arbitrarily chosen. The effect that any of the pond dummies have on shrimp growth is equal to the value of their coefficient. If the value of the pond in question's coefficient is positive than relative to pond twelve the pond in question has a greater effect on shrimp growth. The expected signs of the pond coefficients are more difficult to predict than are the other variables.

The prediction is more difficult because the impacts on shrimp growth that the ponds in question have are specific to the company being studied and no prior knowledge exists as to the ponds' performance.

Results

The results of the regression analysis are reported in three different tables labeled 1, 2, and 3. Table 1 consists of the effects that the environmental variables have on the weekly level of shrimp growth. Table's 2 and 3 specify the effect that both week and pond dummy variables have on the level of shrimp growth, respectively.

Environmental Variables. Four out of the six environmental variables significantly effected the growth of shrimp. The positive coefficients found on each of the three feed variables imply that the addition of more thirty, thirty-five or forty percent protein feed results in a greater amount of shrimp growth. Thirty-five percent protein feed was shown to have the largest impact on growth followed by the thirty percent feed. The coefficient for the forty percent protein feed was greater than that of the thirty percent feed and less than the thirty-five percent feed but did not have a t-statistic that was significant. Specifically, my estimates suggest that a one hundred pound increase in the amount of thirty-five percent feed administered to a pond increases the amount of shrimp growth per week by 2.9 percent. The effect forty percent and thirty percent feeds have on shrimp growth is less, with a one hundred pound increase in forty percent feed increasing shrimp growth per week by 1.2 percent and thirty percent feed increasing shrimp growth per week by 0.79 percent. The results suggest that using more thirty-five percent protein feed as opposed to thirty and forty percent feeds will generate the best results for shrimp farmers.

Returning to Table 1, the estimates for the remaining coefficients are appealing to shrimp farmers. The effect of water temperature on shrimp growth is positive and statistically significant. The estimates indicate that a one percent increase in weekly temperature will increase the amount of shrimp growth by 13.44 percent. The coefficient for salinity, a factor that farmers can control better than temperature, is estimated to be negatively related with shrimp growth and has a t-statistic that is also statistically significant. A one percent increase in the salinity of the pond is estimated to decrease shrimp growth by 2.66 percent per week. Finally, the coefficient for ammonia was negative as anticipated but not statistically significant. Unionized ammonia's effect on shrimp growth was not expected to be statistically significant because the pond manager closely regulates its concentration in the water and does not allow it to fluctuate too greatly. The reason a pond manager closely monitors its levels is because of the fact that unionized ammonia is highly toxic to shrimp.

Table 1. Environmental Variable Estimates of the Weekly Level of Shrimp Growth. Dependent Variable: Ln (Weekly Size)

Independent Variable	Model
Constant	-36.70904*** (12.57012)
40% protein feed	0.000124 (1.474360)
35% protein feed	0.000219*** (4.511484)
30% protein feed	0.000077*** (2.911269)
Ln(temperature)	13.41475*** (17.86617)
Ln(salinity)	-2.655541*** (5.797438)
Ln(ammonia)	-0.037953 (-1.535685)
R^2	0.90
Observations	426

t-statistics are reported in parentheses below the parameter estimates.

* Significant at the 10% significance level or better.
** Significant at the 5% significance level or better.
*** Significant at the 1% significance level or better.

Week Dummy Variables. Another objective of this study was to empirically determine what the change in the weight for the average shrimp was from week to week. Information of this type could help farmers figure out the weeks where total shrimp weight increased by the greatest and least amounts. Farmers could then use weekly growth measurements for forecasting purposes to determine how long to keep shrimp within ponds before their growth begins to slow.

The results (Table 2) showed that, relative to week one, shrimp growth decreased during the second and third weeks and then significantly increased for the remainder of the weeks. The amount that the total weight increased by did not increase at an increasing rate, but varied depending on the week number. Following week three, the growth of shrimp from one week to the next increased at an increasing rate as compared to week one. Total shrimp growth consistently increased until week twelve after which point growth in the average shrimp slowed and began to increase at decreasing weight increments until week seventeen. Over the course of weeks two to eleven, shrimp growth reached its maximum at week eleven relative to week one. The coefficient for week eleven can be interpreted as: By leaving shrimp in the pond until week eleven, the total weight of the average shrimp will be 212% greater than the total weight of the average shrimp in week one.

A rebound in total shrimp growth resulted following week sixteen and the weight of the average shrimp increased successively until week twenty-one. The interpretation of week twenty-one is that, by leaving the shrimp in the pond until week twenty-one, the total weight of the average shrimp will be 285% greater than the total weight of the average shrimp in week one. Following week twenty-two, up until the final week, the size of the average shrimp increased but in decreasing increments.

The negative coefficients for weeks one and two are questionable because of human error that was involved in their determination. Workers estimated the weight of the shrimp for weeks one through four instead of weighing them with a scale. The reason the shrimp were not weighed was because the shrimp were too small to

Table 2. Time Series Dummy Variable Estimates of the Weekly Level of Shrimp Growth. Dependent Variable: Ln(Weekly Size)

Time Dummy Variable	Model
week 2	-0.570205*** (3.25)
week 3	-0.316935* (1.75)
week 4	0.111063 (0.58)
week 5	0.419222** (2.07)
week 6	0.922253*** (4.49)
week 7	1.273216*** (5.90)
week 8	1.671340*** (7.08)
week 9	1.849174*** (7.29)
week 10	2.018197*** (7.41)
week 11	2.120880*** (7.96)
week 12	1.959548*** (7.89)
week 13	1.773800*** (7.62)
week 14	1.646419*** (7.49)
week 15	1.676146*** (7.69)
week 16	1.495714*** (6.99)
week 17	1.927380*** (9.17)
week 18	2.114139 *** (9.99)
week 19	2.411184*** (11.06)
week 20	2.790638*** (12.42)
week 21	2.849907*** (12.64)
week 22	2.839996*** (13.15)
week 23	2.682277*** (12.86)
week 24	2.576332*** (13.26)
week 25	2.351900*** (12.34)
week 26	2.106696*** (10.89)
week 27	1.616070*** (7.50)

t-statistics are reported in parentheses below the parameter estimates.
* Significant at the 10% significance level or better.
** Significant at the 5% significance level or better.
*** Significant at the 1% significance level or better.

accurately weigh. Estimation introduces the possibility for human error which is probably what is seen with the negative coefficients for weeks one and two.

The increasing growth of shrimp at an increasing rate that followed week sixteen can be explained by the mini-harvests that the company performed in many of

its ponds during week sixteen. These harvests provided many benefits to the remaining shrimp that improved their ability achieve greater weekly growth levels. The benefits included; added space to grow in, decreased accumulation of fecal matter in the pond, and less competition facing incumbent shrimp for access to feeds.

Pond Dummy Variables. The final objective of this study was to empirically determine the difference in shrimp weight at harvest from pond to pond. Table 3 provides the results for final shrimp weights and the respective coefficients for each pond relative to pond twelve.

Six of the sixteen ponds produced final shrimp weights that were statistically significant at the ninety-nine percent confidence level or better. The average final weight for shrimp in ponds two, nineteen, thirteen, three, and fifteen produced weights that were significantly lower than the average final weight of shrimp in pond twelve. Conversely, pond ten was the only pond to have a significantly greater final weight for shrimp compared to pond twelve's. The interpretation of pond tens coefficient is that: By growing shrimp in pond ten, the total weight of the average shrimp will be thirty-one percent greater than if it is grown in pond twelve.

Table 3. Pond Dummy Variable Estimates of the Weekly Level of Shrimp Growth. Dependent Variable: Ln(Weekly Size)

Pond Dummy Variable	Model
pond 2	-0.801353*** (3.60)
pond 19	-0.483756** (2.25)
pond 8	0.115427 (0.78)
pond 7	-0.170652 (1.19)
pond 9	0137531 (0.93)
pond 13	-0.565643*** (3.15)
pond 4	-0.154828 (1.11)
pond 3	-0.524988*** (2.73)
pond 15	-0.548717*** (2.85)
pond 1	0.128609 (0.94)
pond 5	0.004307 (0.03)
pond 6	0.008816 (0.07)
pond 11	0.115758 (0.87)
pond 14	-0.066594 (0.49)
pond 10	0.307140** (2.31)

t-statistics are reported in parentheses below the parameter estimates.
* Significant at the 10% significance level or better.
** Significant at the 5% significance level or better.
*** Significant at the 1% significance level or better.

Conclusion

This paper presents qualitative findings that explain the factors responsible for the development of the shrimp aquaculture industry, along with empirical results suggesting that shrimp feeds, water temperature, water salinity, week number, and pond number, significantly affect the level of shrimp growth.

The qualitative analysis cites technological advancements, increases in supply and demand, decreases in shrimp prices, vertical integration of shrimp farms, and the ability of farmers to differentiate the shrimp they supply to the market, as the major factors responsible for the evolution of the shrimp industry. Feed developments, water circulation systems, farming methods, and hatcheries, and are the most notable technological advancements and each one has contributed to improvements in farming techniques. The most important aspect of these advancements is that they have decreased the costs of shrimp farming which has sparked both foreign and governmental investment into the construction of ponds. As a result, the establishment of more shrimp farms has translated into greater quantities of farmed shrimp placed on the world-wide market. A greater amount of shrimp placed on the market has meant reduced prices for shrimp and increased consumer demand. Fortunately for shrimp aquaculture, they have been the primary supplier of the increased market demand since the wild-catch of shrimp has leveled off.

The results from this paper also show that the ability of farmers to differentiate their product, and the gains farmers have realized from vertically integrating their farms, has helped in the development of the shrimp industry. The differentiation of shrimp in terms of their sizes and species has given farmers a comparative advantage over the wild-catch because of the wild-catch's inability to differentiate shrimp. Farmers have capitalized on this characteristic by using the versatility that differentiation gives them to better adjust to market changes in both the tastes and preferences consumers express. By vertically integrating firm operations, farmers

have been able to decrease their transaction costs and operate more efficiently. The farmers have also reduced their dependence on external sources of grow-out products which have been an area of uncertainty at times because of price volatility and supply availability.

The results for the shrimp growth model suggest that feed type, water temperature, water salinity, week number, and pond number all significantly affect the level of shrimp growth. The results were supportive of previous studies that looked at these explanatory variables with the difference being that the previous studies focused only on one variable's impact on shrimp growth, ceteris paribus.

The positive coefficients for all three feeds were expected because it is logical for the average shrimp weight to increase from one week to the next when the amount of feed administered to the pond increases. The logic behind the subsequent growth following increased feed is that the added nutrients supplied by the extra feed provide more energy for shrimp growth.

The results showed that the thirty-five percent protein feed, as compared to the forty and thirty percent feeds, had the greatest impact on the weight of the shrimp. These results were similar to previous studies that cited thirty-two percent protein feeds as most significantly influencing shrimp growth. The conclusion that can be drawn form this finding is that shrimp farmers can conserve on feed costs by using thirty-five percent protein feeds as opposed to the more expensive forty percent feeds when raising shrimp. The reason being two-fold: Thirty-five percent feeds are cheaper than forty percent feeds, and the thirty-five percent feeds increase total shrimp growth to a greater extent than the other feeds.

With regard to temperature's effect on shrimp growth, my findings suggest that a positive and statistically significant correlation exists between the two variables. These results for temperature are supportive of the previous literature because the average water temperature in this study was less than that cited for optimal shrimp growth. Previous literature stated that shrimp growth is fastest at temperatures of

thirty degrees Celsius while the average temperature for this study was 29.23 degrees Celsius. Therefore, my findings indicate that a shrimp farmer can improve shrimp growth in their ponds by increasing the water temperature by approximately one degree Celsius.

From the results it was clear that salinity had a negative and statistically significant effect on the growth of shrimp. The negative coefficient was supported by previous literature when comparing our studies average salinity to that suggested in other studies. The average salinity in this study, twenty-five parts per thousand, was greater than the optimal amount specified for shrimp growth by previous studies of five to fifteen parts per thousand. The results suggest that by decreasing the salinity in a pond, farmers can improve upon the average weight change of the shrimp during the harvest.

Although unionized ammonia's influence on shrimp growth was not statistically significant, its coefficient was negative as predicted, because unionized ammonia was a known toxin to shrimp. The reason it was not statistically significant was most probably because farm managers could control its levels through the use of fertilizers. By regulating its levels in the water, unionized ammonia showed little variance and therefore did not appear to play a significant role in effecting shrimp growth. If its levels were permitted to fluctuate, unionized ammonia would most probably have had a significant coefficient.

The numerical results for the weekly dummy variables offer pond managers a unique look at how the total weight of the average shrimp changes from one week to the next. The results for the time-series dummy variables suggest to shrimp farmers that they should harvest their ponds prior to week twenty-two. The reason harvesting should occur before week twenty-two is because the increases in shrimp growth that are seen following week twenty-two increases at a decreasing rate. By leaving shrimp in ponds past week twenty-two, farmers would be adding expensive feeds to the ponds

and earning less returns on their harvest because of depressed levels of shrimp growth.

The results for the cross-sectional pond tests suggest that shrimp farmers can achieve increased growth levels by selecting particular ponds to raise their shrimp in. The reasoning behind this hypothesis is that certain ponds performed significantly better relative to the reference pond while others performed significantly worse. Therefore, if particular ponds account for better growth performances, as suggested by the data, farmers should stock those ponds with greater amounts of shrimp larvae to achieve better final harvests. In order to confirm this hypothesis, further testing must be conducted for different annual cycles to see if specific ponds produce significantly better results.

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