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Sea-Surface Temperature Related Fisheries and Resource Markets

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SEA-SURFACE TEMPERATURE RELATED
FISHERIES AND RESOURCE MARKETS

BY

JEFFREY MICHAEL RASINSKI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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ABSTRACT

This thesis addresses the potential application of sea-surface temperature (SST) data to economic resource markets. It considers the revolution in technology and the accessibility of timely, accurate SST observations for resource markets. Specifically, it addresses issues related to pelagic fisheries and the fish meal industry. The thesis presents a discussion and overview of the upwelling ecosystem of Peru and the Peruvian anchovy (*Engraulis ringens*) including quantitative analysis and forecasts for the fishery and fish meal prices. This analysis is used to demonstrate the commercial application and relationship between SST and related resource markets. The thesis establishes a bioeconomic statistical model and correlation coefficients between the variables including SST, fish catch, fish meal production, and protein meal prices. The study tests the relationship between SST observations and fish catch and fish meal production. It also addresses the potential problem of overexploitation which may result from using SST data to increase yield. Wise management of these resources may also be improved through the techniques involved with SST modeling.
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CHAPTER I
INTRODUCTION

Statement of the Problem

Modern developments in sea-surface temperature (SST) monitoring have provided us with an unparalleled ability to study marine systems and the activities which depend upon these resources. Data obtained from the satellite sensors provides an enormous amount of readily accessible, accurate sea-surface temperature (SST) measurements. Although much of the data collected has increased our knowledge of these systems, the economic implications of these findings have not been explored in great detail.

Fisheries management and economics are complicated by the fact that fish exist in a medium that is subject to natural oscillations and variability beyond human control. The variable nature of small, shoaling pelagic fish species makes it difficult to develop or adopt a traditional population dynamic model (Csirke 1989). As a result, models used to forecast these fisheries should consider the uncertainty generated by environmental variability. Sea-surface temperature has been demonstrated to be a key parameter in determining the productivity of pelagic fisheries in this changing environment (Mendelssohn and Mendo
Although sea-surface temperature is only one of the many variables that influence pelagic fisheries, it has the potential to enhance and improve models used to forecast fisheries production. Sea-surface temperature serves as an indication of bottom water upwelling and the abundance of nutrients so anomalies may indicate marine regions that are unstable or incapable of sustained exploitation. As a result, temperature fluctuations may be associated with changes in the abundance and distribution of fish populations. It may be possible to forecast the catastrophic event known as El Niño, since it is preceded by warm SST anomalies in the Eastern Pacific (Rasmusson 1985). Previous models have demonstrated that the negative impact on coastal upwelling fisheries can be anticipated by SST anomalies and changes (Pauly and Tsukayama 1987). The warm, nutrient deficient waters associated with El Niño lead to declining fish stocks as well as the migration of key species from coastal waters (Idyll 1973).

El Niño causes many negative impacts such as reduced upwelling and nutrient availability resulting in slower growth rates. These impacts have been studied in great detail and the economic consequences of the impacted fisheries have been directly linked to this warming event (Glantz 1984). This thesis builds upon this foundation of research and attempts to develop statistical models to
correlate SST with fish catch, fish meal production, and fish meal prices. It also provides a forecast model to estimate the price of fish meal.

Hypotheses

It is hypothesized that SST data can be applied to statistical forecast models to estimate fish catch and abundance. Additionally, it is hypothesized that SST data can be correlated with fish meal production and prices.

This study will focus upon the application of the distribution of SST and its relationship to the distribution of the industrial fishery of Peru. Forecast models will be developed to project the impact of SST oscillations. The expected results may identify economic areas that are influenced by variations in surface temperature.

This thesis will review the disruptions caused by El Niño/Southern Oscillation (ENSO) in terms of the pelagic, industrial fisheries, specifically the Peruvian anchovy (Engraulis ringens). For the purposes of this thesis, the term anchoveta will be used in reference to the entire Peruvian industrial fishery for the anchovy or the entire population of anchovy itself. The terms anchovy and anchovies are used in specific reference to the anchovy fish species. The analysis involved in this study will seek to identify the correlation between fish catch and SST. A secondary objective is to regress the production and price of
fish meal obtained from the Peruvian anchovy with SST. In order to accomplish this, the analysis will also consider fish meal's role in the world protein meal market including competition from soybean meal. The results will evaluate the use of SST analysis to forecast fish catch and fish meal production.

Significance of the Study

Although sea-surface temperature analysis provides inherent value to the scientific fields, it holds considerable promise for the future of economic forecasting. SST analysis has been used in other commodity fields to forecast weather conditions and potential crop yields (Toole 1984). Although atmospheric conditions may change dramatically on a daily basis, oceanographic condition follow seasonal patterns and remain comparatively stable due to water's greater thermal capacity. Thus, the consistency of surface ocean temperature relative to the rapidly changing atmospheric conditions, makes SST analysis potentially more reliable as a forecasting variable.

Sea-surface temperature analysis may be used to locate migrating fisheries that follow changes or consistencies in the surface temperatures (Idyll 1973). The data may be used to guide the activities of the world's fishing fleets thereby providing greater efficiency. Therefore, ocean temperatures that are associated with certain pelagic species, such as
tuna, may be used to estimate the biological productivity and perhaps guide fishing efforts to these areas. This can be done by locating the appropriate SST with remote sensing, following these isotherms where the fish are known to be located, and testing the frequency of species distribution (Harris 1989). Improvements in fleet operation may also serve to influence the price of fish meal and related marine resources. Additionally, SST models could lead to increased competition among the fishing sector to allocate the existing fisheries or alternatively reduce the fleet size without adversely affecting total catch.

The application of SST in forecast models provides an enormous economic potential. Forewarning of environmental conditions may enable resource managers to increase the stability of certain fish stocks and avoid resource depletion. SST analysis can also be used to guide the activities of open water mariculture operations. Knowledge of upcoming events will provide an edge to commodity traders on the world's resource markets. Thus, SST analysis provides both an environmental and economic indication value that can be used to model the probability of species distribution and relevant market conditions.

**Thesis Outline and Structure**

This thesis is comprised of two different sections. The first section, covering chapters I and II, provides the
framework of the problem, the reason for the study, the hypotheses that are to be tested, and a detailed literature review. The literature review provides the reader with a qualitative discussion of the issues covered in the thesis.

The second section of the thesis is dealt with in chapters III and IV. This latter half of the thesis provides a description of the methodology used in the study, the analysis that was undertaken to test the stated hypotheses, and the results of that analysis. With the foundation that was laid in the first half of the thesis, the second section engages quantitative and statistical analysis to test the original hypotheses that were stated in the first chapter. The last chapter presents the findings together with a set of recommendations.

The following chapter presents the various elements related to the Peruvian anchoveta. In this way, a foundation is established so that the full impacts of El Niño and the increase in sea-surface temperature may be understood. This chapter describes the biology and ecology of the Peruvian anchovy (Engraulis ringens), the upwelling ecosystem of Peru, the impact of El Niño on the ecosystem and the anchoveta, the history of fisheries management in Peru, the collapse of the Peruvian anchoveta, and fish meal's role in the world's protein meal market.
CHAPTER II
LITERATURE REVIEW

There has been a plethora of literature written about the El Niño and its effects on the coastal ecosystem of Peru. El Niño has been shown to disrupt the chemical and physical properties of seawater resulting in a marked impact on the growth and location of both recreational and industrial pelagic fish species (Squire, 1987) (Idyll, 1973). El Niño interferes with the upwelling ecosystem of Peru and leads to a rapid decline in fish populations. This decline is especially prominent in the Peruvian anchovy which forms the basis for a large portion of the world's fish meal industry (Idyll, 1973). The anchovy fishery has been studied in great detail and the SST dependent nature of the fishery is well documented (Pauly and Tsukayama, 1987). Both the location and abundance of anchovy schools are contingent on SST and the resulting upwelling.

The Biology and Ecology of the Peruvian Anchovy

The Peruvian Anchovy (*Engraulis ringens*) is a small, shoaling, pelagic species of fish that inhabits the waters above the continental shelf off western South America.
Although the anchovy habitat extends from 4° south latitude to over 42° S latitude, the principal area of concentration exists to the north (Mathisen 1989). Its primary range overlaps the region of the strongest coastal upwelling off the coast of Peru. This corresponds to a range from 4° to 14° S latitude and out to a distance of 75 kilometers (km) from shore (Muck 1989). Thus, this main anchoveta region (MAR) represents a total range of some 100,000 square kilometers (Muck 1989). Within this region, the Peruvian anchovy forms vast schools in a depth of water between 20 and 40 meters (Mathisen 1989). The anchovy also tends to concentrate in the northern and central portions off the coast of Peru (Mathisen 1989). Most of the commercial catch is taken within the first 10 kilometers from shore and schools do not form below 40 meters deep (Mathisen 1989).

Although the anchovy contains up to three year-classes, heavy exploitation, natural mortality, and predation results in most fish belonging to the first or second year-class (Paulik 1981). Given ideal conditions, the Peruvian anchovy can live up to 42 months and reach up to 20 centimeters in length (Palomares et al. 1987), but most do not naturally live beyond 25 months (Paulik 1981). The average adult fish weighs 20 grams and reaches a length of 10-15 centimeters (Murphy 1981). The fish are recruited into the fishery between 3 and 5 months of age when they are only 3.75 to 4.75 centimeters in length (Pauly and Palomares 1989).
Figure 1: Distribution of anchovy stocks in main anchoveta region (MAR)
(Source: Pauly and Tsukayama 1987)
A large percentage of the population is sexually mature by the end of the first year (Paulik 1981). Thus, the anchovy is a fast growing fecund species that, under the right conditions can reach enormous populations.

Before human exploitation decimated the stocks of anchovy, this fish supported the largest single-species fishery in the world. It was estimated that populations of the fish ranged from 20 to 30 million metric tons (mmt) (Mendiola 1989). Given the huge population size and the rate of reproduction of the anchovy, this species dominates the Peruvian upwelling ecosystem and forms the second level of the food chain. It is eaten by fish, whales, porpoises, squid, sea lions, guanobirds, and other seabirds and is also subject to human exploitation (Murphy 1981). The horse mackerel is the principal predator of the anchovy followed by avian predation (Pauly and Palomares 1989). Although the guanobird was once a primary consumer of anchovy, this population have declined with the collapse of the anchoveta.

Estimates suggest that the Peruvian anchovy would need to convert 2-3 percent of the total primary productivity to generate its huge population size (Chavez et al. 1989). If a typical ten percent trophic transfer is used then the anchovy would need to consume 10-30 percent of the total primary productivity to convert it to the 2-3 percent of biomass (Chavez et al. 1989). These impressive figures shed some light on the enormous size of the anchovy population and
the importance it plays in the upwelling ecosystem. At the
height of the Peruvian anchoveta, 1,500 modern vessels caught
over twelve million metric tons (mmt) of anchovy, representing one-fifth of all fish caught in the world (Canby
1984). Once spoilage at sea and unloading and processing are
taken into account, actual catch figures could range from
13-14 mmt (Idyll 1973). In past years, the anchovy fishery
provided over 38 percent of the world's fish meal used in
animal feed (Sorenson 1983). Even with the decline of the
anchoveta, this species still dominates the biomass of the
ecosystem.

The Peruvian anchovy exhibits an interesting method of
feeding. This species is capable of switching from
phytoplankton to zooplankton (Mendiola 1989). Larval
anchoveta feed on phytoplankton immediately as their yolk-
store of nutrients is almost non-existent (Muck et al. 1989,
Idyll 1973). The anchovy switch over to feeding on
zooplankton when they reach the post larval and juvenile
stages. Then, these fish switch back to filtering
phytoplankton in the later adult stage (Mendiola 1989). This
ability to switch method of feeding may be a natural
evolution to reduce the competition for food among the
various age groups.

Another interesting behavior that can be observed is the
method of diel, or twice a day, feeding. The fish form large
schools during the day which dissolve at night as the fish
feed individually (Mathisen 1989). A study found that the anchovy feeding begins about 11:00am and ends about 12:00am lasting for approximately 13 hours (Pauly et al, 1989). Most of the feeding occurs at night and then the fish reform schools at dawn (Muck et al. 1989). This tendency to school to a depth of 40 meters during the daylight hours may be an evolutionary response to reduce mortality through predation.

The anchovy spawn throughout the year although two distinct period of increased spawning do occur. One of these periods occurs during September, October and November (Mathisen 1989). This is the major spawn which occurs in the months with the lowest environmental variability (Muck 1989). The second minor spawn occurs during the months of January and February when the range of SST tends to be the greatest (Mathisen 1989). Hence, the seasonal pattern of spawning maximum is largely explained by oceanographic variability.

The spatial distribution of phytoplankton and zooplankton (the food source for the anchovy) is directly related to oceanographic conditions such as turbidity and SST. The presence of phytoplankton of the correct size and the appropriate concentrations is necessary for the survival of the larval fish. Additionally, egg development and egg cannibalism is dependent upon SST and water conditions (Pauly 1989). Thus, the anchovy spawn inshore where higher phytoplankton concentrations can be found and are available for the newly hatched anchovy larvae (Muck et al. 1989).
The tendency for the anchovy to spawn year-round and in those months when the natural variability is the lowest is an evolutionary adaptation to cope with a changing environment (Muck 1989).

**Sea-Surface Temperature and the Anchovy**

The spatial distribution of Peruvian anchovy is contingent upon the availability of nutrients for the prey on which it feeds. Concentrations of nutrients are related to the upwelling process and subsequent SST. Waters with a temperature less than or equal to 17° Celsius correspond to those nutrient-rich waters that are upwelled (Muck et al. 1989). As a result, the anchovy congregate near the 17° Celsius isotherm. As the upwelled waters are moved offshore, they mix with warmer surface water and the nutrients are depleted. The 20° Celsius isotherm serves as the boundary between the nutrient-rich and nutrient-poor surface ocean water. Anchovy predators, such as the mackerel and horse mackerel are found at this boundary (Muck et al. 1989).

As a result of their affinity for water temperature near 17° Celsius and upwelled nutrients, the range of the anchovy varies seasonally depending on the strength of upwelling. Upwelling in the Peruvian ecosystem is the strongest in the Austral winter during the months of May, June, July, and August (Paulik 1981). With the advent of stronger upwelling and available nutrients, the range of the anchovy increases
and the population becomes less dense, spread over a greater area (Paulik 1981). During this time most of the Peruvian waters are cold (less than or equal to 17° Celsius) and the range of anchovy extends to 60 nautical miles from shore (Muck et al. 1989). The summer brings the opposite conditions to the ecosystem as waters warm and the effective range is reduced to 2 percent of the winter range. The offshore limit is reduced to under 10 nautical miles (Muck et al. 1989). As a result, commercial exploitation of the Peruvian anchovy is much easier and more profitable in the summer months. The fish are more concentrated and school closer to shore and the port cities of Peru.

Many species of fish exhibit a similar preference for a given range of SST as the Peruvian anchovy. Most notable are other species belonging to the Clupeoid Family, the same as that of the Peruvian anchovy. It was found that ocean conditions, specifically SST, could help explain the distribution, year-class production, and yield of the Pacific sardine (*Sardinops sagax*) (Smith 1979). Another study found a strong linear relationship between SST and the schooling of sardine (Mendelssohn and Cury 1987). Conceptually, it makes sense that SST may serve as an indication for the rate of upwelling in an upwelling ecosystem. Furthermore, the stronger the upwelling, the more nutrients are available for primary productivity and trophic transfer. As a result of this productivity increase, Mendelssohn and Cury found that
colder SST (stronger upwelling) was consistent with a lagged increase in the catch per unit effort (CPUE) of certain pelagic species (Mendelssohn and Cury 1987). This lag ranged from 4 months to a full year depending upon the species of fish being caught (Mendelssohn and Cury 1987). Thus, there seems to be a relationship between oceanic conditions, specifically SST in certain cases, and the distribution, fishing success, and recruitment (Radovich 1959).

Despite the poikilothermic, or cold-blooded, nature of pelagic, marine fishes, there may be a range of SST that favors the metabolic requirements of various species (Squire 1987). There may be an optimal range of SST associated with the spatial distribution of certain species that may be indirectly linked to upwelling or other processes. Therefore, SST may be used as a statistical measure in a model to forecast certain fisheries production and spatial distribution. Coastal fronts may be located and SST may be analyzed using infrared sensors on satellites to assist fisheries forecasting (World Fishing 1992). This data can be used to estimate production or the probable locations of key species, such as the jack mackerel, which schools in waters of 15° Celsius (Harris 1989).

The decline of the California sardine industry serves as an additional example of a fishery that may be considered SST dependent. This fishery supported catch figures on the order of 600,000 tons annually during the 1930's and 1940's (Paulik
1981). For an unknown reason, water temperatures began to fall slightly in the early 1950's and catches decreases to around 150,000 tons annually (Paulik 1981). With the decrease in the sardine population, the Northern anchovy (Engraulis mordax), populations began to increase (Squire 1987). This led to speculation that "the real cause of the disappearance of the California sardine was a climatic change" (Smith 1979).

**The Peruvian Upwelling Ecosystem**

In terms of net primary productivity, or the amount of carbon that is fixed from biological activity, much of the top layer of the ocean is a veritable desert. Sea-surface temperatures are at a maximum here and nutrient concentrations are at a minimum. Two distinct exceptions to this scenario are oceans waters above continental shelves and zones of upwelling. Productivity increases over continental shelves as currents and turbidity increase the vertical mixing and recycling of nutrients (Stowe 1982). Upwelling is the process by which colder, deep, nutrient-rich waters are essentially pumped to the surface by physical oceanographic and other processes (O'Brien et al. 1981).

The processes involved in bringing colder, deep, nutrient-rich water to the surface include surface winds, the coriolis effect, the Eckman spiral, surface barometric pressure, currents, and land topography (Thompson 1981).
Surface winds moving off of a continent can push waters away from the continent inducing an updraft of deeper water to take the place of those waters that have been pushed offshore. Essentially, this divergence (Ekman spiral) is created by the surface winds which cause the upwelling (Mooers 1978). As a result of Earth's rotation, the Coriolis Effect deflects surface waters off the western side of continents and moves them to the left in the Southern Hemisphere and to the right in the Northern Hemisphere westward across the ocean (Cane 1983). As a result, extensive upwelling is found on the western sides of continents near the equator (Figure 2) (Thompson 1981). For this reason, productivity is generally greater in the eastern equatorial oceans due to the shallower thermocline (Thompson 1981). These currents creates an updraft whereby deeper waters are brought to the surface. The cold, deeper waters are upwelled from beneath the photic zone (100-300 meters) where the waters are rich in dissolved nutrients that have built up over time (O'Brien et al. 1981). Additional factors may also influence upwelling. Continental and submerged topography can also deflect surface ocean currents and create localized upwelling.

Regions of upwelling are most noted for their high rates of primary productivity in comparison to the open ocean. Although upwelling regions only account for 3 percent of the total ocean surface, they produce 38 percent of the ocean's
total exploitable productivity (Goulet 1978). As soon as nutrient-rich, colder, deep water reaches the surface photic zone, the nutrients provide an ample supply for primary productivity of phytoplankton and zooplankton. This primary productivity, in turn, forms the foundation for a productive food chain. Therefore, these zones of upwelling can have primary productivity rates on the order of 1 gram of Carbon per meter square per day (g C/m²/day) (Thompson 1981). These rates are much higher than the average productivity of the open ocean which is 50 g C/m²/year (Thompson 1981). Additionally, these fast growth rates lead to shorter food chains and more efficient trophic transfers of biomass. Major areas of upwelling include the west coast of the United States, Peru-Chile, northwest and southwest Africa, and the Arabian coast (Thompson 1981).

The oceanographic region off the coast of Peru serves as one of the most productive fisheries in the world. Environmental processes combine to create the strongest of five areas of oceanic upwelling (Canby 1984). The prevailing trade winds accelerate the movement of the water westward along the equator (Eckholm 1986). As the winds move surface water away from the coast, the rapid departure induces an updraft of deeper seawater to take its place. Thus, a localized area of upwelling is formed bringing cold, deep, nutrient rich waters adjacent to the 1,475 miles of Peruvian coastline (Idyll 1973).
The upwelling region is part of the Peru Coastal Current which is actually a branch of the deeper oceanic Humboldt Current (Idyll 1973). Both of these currents follow the coast northward over the narrow continental shelf in their Pacific gyre. A countercurrent runs between these two currents as a result of oceanic divergence. Additionally, there is a fourth current which flows to the south beneath all three of the surface currents (Thompson 1981). It is the current/countercurrent system that creates localized gyres which support blooms of phytoplankton and zooplankton (Paulik 1981). These gyres enable populations of phytoplankton to build and reproduce, supporting the basis of the productive food chain.

Observations of the cold Peru Current can be traced historically to the Spanish conquistadors who used the waters to cool drinking flasks (Rasmusson 1985). Initial speculation placed the source of the current at the Antarctic due to the cold, constant temperatures (Rasmusson 1985). Even though the current lies just 22° N of the equator, water temperatures in the upwelled waters are the coldest observed at that latitude (Idyll 1973). These temperatures can remain as cold as 10° Celsius (Idyll 1973). It is the cold upwelled water rich in nutrients that causes the low SST and high productivity in the Peruvian ecosystem.

The prevailing easterly trade winds that push waters westward over the tropical Pacific also have a pronounced effect on atmospheric circulation. These winds create a
Figure 2: Map of Pacific surface ocean currents
(Source: O'Brien et al. 1981)

Figure 3: Map of Peru (Source: Arntz 1984)
frictional drag on the ocean and stack waters on the western side of the Pacific Ocean (Rasmusson 1985). As the waters are piled up, the warm surface layer increases and depresses the thermocline (Ramage 1986). The thermocline, or the boundary between the well mixed surface layer and the colder, deeper layer, actually becomes deeper as you move from east to west in the equatorial Pacific (Ramage 1986). The South American thermocline has a shallow depth of 50 meters compared to 200 meters in the west Pacific (Ramage 1986). The upwelling in Peru contributes to the shallow depth of the thermocline where temperature gradients can reach a difference of 10°C (Cane 1983). The stacking of waters also creates a difference of sea level in the Pacific. Since water is usually pushed toward southeast Asia, the water level in the western Pacific is about 0.5 meters higher compared to the water level in the eastern Pacific (Rasmusson 1985). Waters in the upwelled region adjacent to Peru are colder and lower than those west of the dateline.

The prevailing sea surface temperature (SST) gradient across the Pacific generates thermal atmospheric circulation and rainfall patterns around the globe (Rasmusson 1985). As the dry, cool air sinks over the cold waters of the eastern Pacific, it is moved west along the equator by the trade winds. The air gradually warms and picks up moisture while it passes over increasing SSTs on its western route. When it reaches the 28°C SST isotherm convective heating begins and the
Evaporated water condenses and precipitates as the air rises. This conventional atmospheric circulation, known as the Walker Cell, creates the abundant rainfall of the tropics in the western Pacific (Rasmusson 1985). It was discovered by the British scientist Sir Gilbert Walker, who made the connection between atmospheric circulation and the Indian Monsoon (Rasmusson 1984). He made the association between atmospheric anomalies and monsoon failure in 1904 as Director-General of Observation in India (Rasmusson 1984).

The true importance of the upwelling for South America is the nutrients that the waters bring to the surface. The deep waters are rich in nutrients such as phosphate and nitrite (Rasmusson 1984). The combination of these nutrient salts and surface sunlight drives the primary productivity of the ecosystem. Additionally, the current/countercurrent circulation produces localized gyres which hold the populations of phytoplankton near the upwelled water (Idyll 1973). These ideal conditions enable phytoplankton, the basis of the food chain, to fix carbon by photosynthesis. The phytoplankton in turn support one of the largest pelagic fisheries in the world. The enormous biomass of the fishery is supported by a relatively localized area of upwelling. The rich waters also offer great potential for pelagic fisheries.

The populations of anchovy provide a large source of income to the developing economy of Peru. Even though the
waters off the coast hold a bounty of fish, the desert-like coastal land of Peru offers very little arid land for agriculture (Idyll 1973). However, large populations of guano bird, whose diet is 80-95 percent anchovy, do provide needed fertilizer for the land in their droppings (Idyll 1973). Obviously, the anchoveta is of vital importance to the Peruvian economy.

The Impact of El Niño on the Ecosystem of Peru

The term El Niño, Spanish for the "Christ Child", was originally used by the Peruvian fishermen for the surge of unusually warm water off Peru around Christmastime (Eckholm 1986). Evidence suggests that the El Niño/Southern Oscillation (ENSO) has brought irregular warming to the Pacific since 3000 B.C. (Sorenson 1983). Events in history present facts supporting the regular oscillations in equatorial Pacific SST. Floods occurring in 1100 A.D. which destroyed arid plains in Peru have been attributed to ENSO (Sorenson 1983). Additionally, "eighteenth-century British pirates recorded El Niño's blood-red patches of plankton in their log books" (Sorenson 1983). It would seem that El Niño is an event that has occurred on a regular basis during recorded history.

El Niño is a global event which causes widespread climatic anomalies in temperature and rainfall. El Niño is defined as: "an anomalous oceanic and meteorological event
characterized by the sudden appearance of abnormally warm surface water on the scale of a thousand kilometers off the coasts of Peru and Ecuador" (O'Brien et al. 1981). The Scientific Committee on Oceanic Research uses a stricter definition of El Niño as:

"the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12° S) during which a normalized sea-surface temperature (SST) anomaly exceeds one standard deviation for at least four consecutive months at three or more of five coastal stations (Talara, Puerto Chicama, Chimbote, Isla Don Martin, and Callao)" (Quinn and Neal 1987).

The meteorological term "teleconnection" refers to geographically separated events of great anomaly that are related (Glantz 1984). This term describes El Niño and its impact on global weather and rainfall patterns. El Niño is basically triggered by a relaxation in the surface trade winds which drive the surface currents off the coast of Peru and induce upwelling (Ramage 1986). As the winds relax, ocean movement to the west is reduced and warm waters begin to creep toward the South American coast. The SST gradient including the 28°C isotherm moves east, shifting the convective cell and Walker circulation (Rasmusson 1985). The change in atmospheric circulation alters rainfall patterns bringing drought and flooding to different regions. Warm waters can move 100° longitude to the east at a rate of 200 miles per day (Sorenson 1983). The SST oscillation can disturb the entire marine ecosystem from the Gulf of Alaska to southern Chile (Rasmusson 1985).
Development of a full El Niño follows a set of progressive stages and oceanographic conditions. The first phase regularly occurs in March to May in which the large scale warming begins across the equatorial Pacific. The second stage is defined by the continued warming of SST on a large scale. The third phase is required for an El Niño to be termed mature, or fully developed with SST anomalies existing in December through February. The last phase occurs in May through July when the event begins to fade out and temperature decline (Harrison and Cane 1984). The development of the full El Niño starting in December is consistent with the classical arrival at Christmas.

As it develops, ENSO disturbs the circulation of the ocean and atmosphere resulting in a change in the Walker Cell (Righter 1983). This disruption in convection is known as the Southern Oscillation and was first discovered by Jacob Bjerkens (Rasmusson 1984). He found the link between SST anomalies in the Pacific and atmospheric circulation during the 1957/58 ENSO event (Rasmusson 1984). The International Geophysical Year provided the first understanding of the broad impact of El Niño. Bjerkens also discovered that ENSO SST warming was not isolated in the east Pacific. Ocean warming extended across the Pacific to the dateline in conjunction with weaker trade winds (Rasmusson 1984).

The most notable ecological anomalies are experienced off the coast of Peru during an El Niño year. Thus, sea-
surface temperature (SST) anomalies off the coast of Peru are a primary indicator of El Niño (Toole 1984). A SST anomaly is defined as the deviation in degrees Celsius away from the expected normal SST (Squire 1987). Obviously, temperatures above normal are referred to as positive anomalies and those below normal are termed negative anomalies. El Niño is consistent with the occurrence of positive anomalies for several consecutive months and La Niña is the occurrence of negative anomalies of 2° Celsius for several months (Guillen and Calienes 1981). When the westerly trade winds relax, warm surface waters remain and upwelling stops. This cuts off the supply of cool, nutrient rich waters and El Niño begins to develop. El Niño can develop rapidly as much as 1° Celsius in 2 months and 2° Celsius in 4 months (Toole 1984). Although this does not appear to be an enormous amount of warming, the thermal energy required to raise most of the Pacific equatorial surface waters a few degrees Celsius is significant.

An El Niño causes a variety of additional changes in the chemical and physical properties of seawater, as well as atmospheric circulation and weather patterns. Salinity in the Peru Current can decrease from 35 or 36 parts per thousand (ppt) to 32.7 ppt with the reduction in nutrient salts (Idyll 1973). Dissolved oxygen can also increases from under 1 milliliter at a depth of 30 meters to 1.5 milliliter (Arntz 1984). SST positive anomalies can reach 6° Celsius as
water temperatures exceeded 29° Celsius across the equator (Harrison and Cane 1984). The warm waters may extend off Peru for thousands of kilometers extending over the entire tropical Pacific.

Another result of the change in atmospheric circulation and air masses is the oscillation in surface pressure. ENSO intensity is often measured by the Southern Oscillation Index (SOI) (Brainard and McLain 1987). It is the difference between surface barometric pressure of Easter Island (27°10' S latitude, 109°25' W longitude) and Darwin, Australia (12°26' S latitude, 130°52' E longitude) (Ramage 1986). During an El Niño, the higher SST shifts convection to the east. High pressure forms over Australia which diverts rainfall away from the continent bringing drought. The high Australasia pressure that is generated can also lead to a failure of the Indian monsoon. Lower pressure over Easter Island is followed by increased rainfall and storm activity. Changes in air masses and pressure contributes to the rainfall anomalies associated with El Niño.

El Niño's relaxation in trade winds allows the warm waters to remain in the eastern Pacific. The waters are not pushed away and the sea level rises. Peru experienced a relative sea rise of 15-20 centimeters (cm) in addition to increased storm activity in the 1982/83 ENSO (Righter 1983). Both of these factors led to high coastal erosion and flooding which extenuated economic hardships for the country.
The Galapagos Islands were also subject to a 22 cm rise in sea level in July 1982 (Cane 1983). The combination of destructive floods, crop damage, and collapse of fisheries is especially devastating to the economy of a developing nation like Peru.

The change in conditions of the sea adjacent to Peru favor the migration of foreign and secondary species into the area (Glantz 1981). Species such as yellowfin tuna, dolphinfish, manta ray, tropical crab, skipjack, mackerel and hammerhead shark may all be found in abnormal abundance (Idyll 1973). The warm conditions also tend to favor population explosions of shrimp and scallops for some unknown reason (Canby 1983). The 1982/83 event also brought the warming of the California Current and migration of crab species 1,800 km north of their normal range (McGowan 1984). Higher SST along the west coast of the U.S. shifted the traditional salmon route farther north into Canadian waters (Glantz 1984). Adverse environmental conditions in Peru led to the migration of anchovy populations and other pelagic fish south to Chile. Although El Niño displaces many marine species, it also provides the oceanographic conditions for other species to occupy the niche in the ecosystem.

events of 1951, 1953, 1963, 1969, 1975, and 1983 were all weaker episodes that had less impact on the ecosystem (Rasmusson 1983). The years of 1965 and 1975-1976 corresponded to years of moderate El Niño and the years of 1957-1958, 1972-1973, and 1982-1983 were all strong events (Rasmusson 1983). Since the 1982-1983 event, there was a mild event in 1986 and 1992 has reached the conditions necessary to be classified as a moderate to strong El Niño. La Niña episodes, which are events of abnormal cooling, have been recorded in 1968, 1970-1971, 1974, and 1988 (Guillen and Calienes 1981). The change in chemical and physical properties of seawater during an event drastically alters the Peruvian ecosystem.

Global Impacts of El Niño

It has been determined that ENSO brings many global anomalies to different climates all over the world. Changes in convection in the 1982/83 event brought ten times the normal amount of rain to Equador and Peru causing mudslides and flooding (Arntz 1984). It brought drought to Australia, Indonesia, and South Africa as well as brush fires in Ghana and the Ivory Coast (Glantz 1984). Tahiti was hit by six typhoons and the Indian monsoon failed (Sorenson 1983). Rough storms increased coastal erosion in southern California and flooded its agricultural valleys (Righter 1983). Unusually high SST in the Pacific brought a mild, wet winter
to the continental U.S. (Righter 1983). The event also caused additional rainfall across Brazil leading to bumper crops (Ellis 1990). Estimates suggest that the total global damages of the 1982/83 ENSO were 8.65 billion dollars and resulted in 1,000 deaths (Canby 1983).

El Niño's Impact on the Peruvian Anchovy

The Peruvian anchovy is profoundly impacted by El Niño. During this event, atmospheric and oceanic circulation are altered, curtailing the upwelling and availability of nutrients (Canby 1984). The warm waters associated with El Niño reduce the available habitat for the anchoveta forcing the remaining populations closer to shore where the sea-surface temperature is cooler. This actually makes the anchovy more susceptible to human exploitation which often increases during an El Niño (Csirke 1989). Therefore, it is not uncommon that yields increase while actual stock size is decreasing. As a result of the unfavorable environmental conditions, the Peruvian anchovy populations decline.

The food chain is basically interrupted by the El Niño which essentially curtails the upwelling and phytoplankton growth. As the upwelling is restricted, the warm waters reduce the habitat of the Peruvian anchovy. Warmer, oceanic waters that are associated with predators of the anchovy, such as the mackerel and horse mackerel, are brought much closer to shore increasing the predation on the anchovy.
populations (Muck et al. 1989). The higher SST, low availability of nutrients, increased predation, and reduction in habitat induces stress on the stocks resulting in the decline of the anchovy. Although the anchovy initially congregates in the remaining upwelled areas, this enables fishermen to easily exploit the concentrated stocks (Glantz 1984). Increasing catchability coefficients from the smaller, more concentrated fishing areas closer to shore exacerbates the decline in stock populations (Csirke 1989). Additionally, the reduction in nutrients translated into less food for the remaining anchovies which become emaciated (Palomares et al. 1987).

The occurrence of El Niño causes instability in the ecosystem which leads to fluctuating catches and abundance of various species (Aguero 1987). Although El Niño classically arrives in December or January, its impact in terms of SST anomaly is greatest during the summer months of February and March when the habitat has already been reduced by the seasonal advance of warm water (Guillen and Calienes 1981).

**Fishing Methods and Technology**

Given the pelagic nature of the fishery, the principal means for harvesting the fish is the purse seine. Most boats, or bolicheras, are approximately 100 feet in length with a hold capacity of 300-350 tons (Paulik 1981). These boats use nets approximately 300 fathoms long and 35 fathoms
deep with a mesh size of 10 to 30 millimeters (Aguera 1987). The nets are set with diesel motors and then collected as the catch is pumped to the hold of the vessel (Aguero 1987). To assist with locating and catching the fish, fishermen have continued to upgrade their technology with nylon nets, echo sounders, hydraulic systems, and steel hulls (Aguero 1987). Thus, catch per unit effort (CPUE) has increased over time. Boats normally make one trip per day that can last from 12 to 24 hours in length (Csirke 1989). Fishermen take advantage of the diel, or twice a day, feeding behavior of the fish and begin fishing shortly after daybreak when the commercially exploitable schools of fish have formed (Muck et al. 1989).

**History and Management of the Anchoveta**

The Peruvian anchoveta fishery began in the early 1950's, but the rapid development did not take place until the 1960's in response to increased world demand for fish meal (Tsukayama and Palomares 1987, Paulik 1981). Fish meal is used primarily as an animal food supplement for both conventional agriculture and aqua/mariculture. The fishery did provide canned and preserved fish for troops during the Second World War, but the massive expansion had not yet taken place (Paulik 1981). Many assets were relocated to Peru after the collapse of the California sardine industry in the 1930's. By 1963, Peru was the largest producer of fish meal in the world (Glantz 1981, Paulik 1981). Prior to 1968,
management of marine fisheries in Peru was shared by several agencies including the Ministry of Finance, the Ministry of Agriculture, the Ministry of the Navy and the Ministry of Labor (Hammergren 1981). Primary responsibility for managing the fisheries was not delegated in a single agency. Consequently, interests among the involved agencies often conflicted and overlapped. Despite the nebulous control of the fishery, changes in the nature and quantity of anchovy prompted studies of the fish stocks in 1964 (Hammergren 1981). During this time, the number of boats increased dramatically. By 1964, the Peruvian anchovy fleet had grown to 1,623 vessels (Aguero 1989). In order to protect the populations of smaller juvenile fish, the first closed season, or veda, was established in 1966 (Hammergren 1981). Although it was not enthusiastically accepted by the fish meal industry, the veda marked an early attempt to conserve the stocks (Hammergren 1981).

Most of the fisheries regulations prior to 1968 did not set a limit on the total allowable catch (TAC). Initial regulations were adopted to restrict fishing activities to a maximum of five days per week (IMARPE 1981). The restricted fishing activity served to protect the smaller juvenile fish usually for one month of the year (IMARPE 1981). There was also a limit to the number of licenses granted to operate processing plants (IMARPE 1981). However, these regulations did not limit catches that could be taken "legally" in the
open season. There was no initial limit set on quantities landing in the allowed season. During the height of the fishing season, boats were capable of landing one percent of the yearly catch in one day (IMARPE 1981). Obviously, fishing intensity and catch limits must be instituted to protect the fish stocks. The excess capacity that was present in the industry indicates that the industry was overinvested resulting in economic inefficiency.

Even though the veda closed a certain season to fishing effort, it did not set limits to the total fish catch in the open seasons. "This produced problems later, as technological improvements along with major increases in the number of boats and factories expanded fishing and fish meal processing capacity, thereby heightening competitive pressures" (Hammergren 1981). Clearly, there was no safeguard against fishing intensity in the open seasons. The first veda was also set in the winter months when the anchovy were more dispersed and catchability coefficients were lower (Hammergren 1981). The terminology of catchability coefficient refers to the degree or ease with which fish are caught given a certain level of effort. Conservation of a fishery did not emphasize the number of fish taken. It concentrated more on the time allotted to the activity of fishing. Unfortunately, increasing effort or intensity in remaining seasons can be just as destructive as year-round harvesting.
By the mid 1960's, the fishery observers were aware that the existing fleet and plant capacity was double what was needed to process the total allowable catch (TAC) (Hammergren 1981). However, national attention was not focused on the problems of the fishing industry. A military coup occurred in 1968 in which Fernando Belaude Terry replaced the former military government (Hammergren 1981). Government involvement in the fishing sector increased and a development boom resulted (Hammergren 1981). Given the critical role of the newly established government and needed economic reform, the fishing sector operated under the government's "laissez-faire" policy (Hammergren 1981).

Fishing policy regarding the Peruvian anchoveta was also influenced by the fish meal interests which employed half of the labor involved in fishing (Hammergren 1981). The industry provided Peru with 35 percent of its total foreign earnings (Hammergren 1981). Fish meal manufacturers dominated the National Fisheries Society, the major political lobbying group for fishing (Hammergren 1981). The combination of political clout and economic strength served to establish fishing regulations that were favorable to the manufacturers. This situation posed a problem in that policies were established based on short-term economic gain as opposed to long-term eco-environmental sustainability. Scientific evidence surrounding the crisis of overfishing did not generate the same interest as immediate revenues.
Management of the Peruvian Anchoveta continued with the Instituto del Mar del Peru, created by the Food and Agriculture Organization (FAO) of the United Nations in 1970 (Idyll 1973). It was formed to research the anchovy stocks and to make management recommendations. The Ministry of Fisheries was created in the same year in an attempt to centralize control of the fishing industry (Hammergren 1981). The Ministry encouraged extensive fishing allowing the industry to continue in the open season after the recommended limit had been exceeded (Hammergren 1981). The enormous effort led to a record catch of 12.5 million metric tons (mmt) in 1970 demonstrating the Ministry's aptitude and ability to generate revenue (Hammergren 1981). The catch was also increased by 300,000 tons to alleviate economic shortcomings in the industry (IMARPE 1981). Obviously, short-term financial concerns were the motivation behind the fishing policy that did not consider the potential harm of exceeding the recommended fishing limit. In fact, the MSY was surpassed long before fishing pressure subsided.

The ill effects of the overfishing surfaced almost immediately with the 1972 El Niño. Despite this occurrence, many still believe that the collapse of the fishery was inevitable given the heavy pressure on the stocks and the decline of recruitment. This recruitment was reaching dangerously low levels as a result of harvesting most of the adult populations of anchovy. This left the small year-class
to spawn. The warning signs of overfishing signaled the potential disaster that was to come as early as 1969. In that year, the populations of larger, mature fish were at a record low (IMARPE 1981). The percentage of small, juvenile fish in a given catch also increased indicating the declining availability of mature fish. This percentage increased from 14 percent to a record high of 62 percent in January of 1970 (IMARPE 1981). The total allowable catch (TAC) of 9.5 mmt in 1970 could be taken by the existing fleet in 130 days, or one half the year (IMARPE 1981). By 1971, the fleet had the potential to land the allowable catch in 90 days compared to an average fishing season of 300 days in the early 1960's (Vondruska 1981). This is definitely not wise or efficient use of the fish resources. Clearly, maximum or optimum efficiency "could be achieved if the catching and the processing capacities worked at full efficiency throughout the year" (IMARPE 1981). Figures demonstrated that the fleet could have been reduced by 20-30 percent without any adverse impact on fish meal production (IMARPE 1981).

The Collapse of the Peruvian Anchoveta

The combination of overfishing and the El Niño decimated the stocks of anchovy. In March of 1971, SST in the eastern equatorial Pacific began to experience positive anomalies signaling the onset of El Niño (Thompson 1981). The following March saw a record level of catch when landings
approached 170,000 tons per day (Thompson 1981). In three years, the anchovy catch declined from over 10 mmt in 1971 to 4.5 mmt in 1972 and 1.5 mmt in 1973 (Hammergren 1981, Sorenson 1983). The fishery declined by 90 percent in this short period of time. Although the IMARPE attempted to curtail fishing in the latter half of 1972, the damage to the fishery had already been done (Hammergren 1981).

The economic infrastructure of the fishing industry began to collapse as the anchovies became more scarce. Clearly the previous boom had drawn an overabundance of investment and capital into the industry. Heavy investment in fishing had created a huge foreign debt that could not be satisfied after the collapse (Hammergren 1981). Estimates proposed that the industry had been overextended by 1,256 boats, 105 factories, and 27,000 workers (Hammergren 1981). The lack of available resources meant bankruptcy for the industry which could not meet its loans and operating costs.

In the case of Peru after the collapse of the anchovy, the government was faced with the problem of reducing the excess capacity in the fleets and plants. The private assets of the anchoveta industry were nationalized in 1972 and the remaining assets were transformed into PESCAPERU, a state operated venture (Castillo and Mendo 1987). PESCAPERU gained control over the anchoveta fleet and fish meal processing plants (Hammergren 1981). This move was made to better coordinate fishing effort and prevent future overfishing.
Figure 4: Major changes in ecosystem after the collapse of anchoveta in early 1970's. The dramatic shifts of species in the ecosystem can be seen starting in the early 1970's.
(Source: Muck 1989)
Official sought to prevent problems like those during the fishing season that occurred in 1970.

The government redirected fishing effort toward the less developed area of food fishing (Hammergren 1981). However, this was complicated by the fact that most of the fishing infrastructure had been geared toward the Peruvian anchovy. This led to a subsequent depletion of those stocks in 1973-75 and virtual disappearance of several species from the Peruvian waters (Hammergren 1981). Additionally, the purse seine fleet attempted to switch to catching a combination of both anchovy and sardine depending on the season (Muck 1989). They hoped to offset losses incurred in the closed season by fishing for alternate species. Unfortunately, it is difficult to curtail fishing once the industry is in place, even if reducing the effort is the right choice. Fishermen and the fishing industry require some degree of economic consistency in order to survive financially.

Eventually, the private assets that had been nationalized by the government under the direction of PESCA PERU were returned to private ownership (Hammergren 1981). A scaledown of the industry occurred throughout the 1970's and the number of factories, vessels, and fishermen continued to decline (Hammergren 1981). Despite efforts to remove capital assets from the industry, many of the vessels and factories were not successfully converted to other fisheries (Hammergren 1981).
The collapse of the anchovy populations also has a broad impact on other species that rely on the fish for food. After the 1957 ENSO, guano-bird populations went from 27 million to 5.5 million (Idyll 1973). Their numbers slowly recovered until the 1965 event arrived again reducing the population to 4.3 million (Idyll 1973). The subsequent collapse in bird populations is not limited to Peru following an El Niño. During one ENSO event, the entire bird population of Christmas Island, estimated at 17 million, disappeared (Righter 1983). Warm, oxygen rich waters bring bacteria and dinoflagellates to the area resulting in toxic "red tide" blooms near the coast (Idyll 1973). ENSO conditions stress the habitat of fish, squid, and turtles and often force them to disperse. An El Niño drastically alters the existing biomass proportions and brings rapid changes in diversity and distribution.

The collapse of the anchovy has had an enormous impact on the biomass of the entire ecosystem of Peru. The anchovy stock has fallen by a factor of 4, closely paralleling the guanobird population (Muck 1989). Numbers of mackerels, horse mackerels, sardines, and pinnipeds have increased (Muck 1989). The entire biomass of the ecosystem has shifted as a result of the collapse of the anchovy in the early 1970's (Muck 1989). Most notably, the stock of horse mackerel, a major anchoveta predator, has risen potentially preventing the anchovy from rebounding from the collapse (Muck 1989).
Fish Meal's Role in the World's Protein Meal Market

The industrial fisheries industry is the largest volume fishery in the world involving an enormous number of producers and species of fish. Products of the industry are limited to three outputs including fish meal, fish oil, and soluble fish protein. However, of these three fish meal comprises the overwhelming majority of the industry. The fish meal industry is a market based upon the reduction of fish to a dried protein commodity which has several uses in other markets.

Fish meal is defined as "a cost-effective, high-protein poultry, livestock, and farmed fish feed ingredient made by cooking, pressing, drying, and grinding fish" (Glantz 1981). Fish meal can be processed from a number of fish species although the source, or supply, of fish can be derived from two distinct categories. The first involves reduction of the whole, ungutted fish into a dried, protein-rich meal. This method is by far the most common involving the utilization of low-value, small, pelagic, schooling fish such as anchovy, sardine, herring, mackerel, and menhaden. Approximately 95 percent of the world's fish meal production comes from these oily pelagics (GTA Fisheries Consult. Ltd. 1989). The small size of these fish is ideal for reduction. Additionally, these large volume fisheries provide an abundant supply for the source of protein for the industry. Obviously, the Peruvian anchoveta is primarily an industrial fishery and the resource is generally reduced to fish meal.
The second source of fish for processing involves the utilization of fisheries waste, or offal. Offal is the term generally used to describe the portions that are not used or wanted after the initial processing step (GTA Fisheries Consult. Ltd. 1989). Traditionally, the term offal was used by the livestock industry to describe the portions of the carcass that are not intended for human consumption. It refers to the bones, internal organs, blood, and lungs. This term is still widely used today. For fish, offals refer to the bones, skin, head, viscera, fins, and tail. These fish wastes are obtained from other finfish markets, such as the salmon or tuna markets, that fillet and process their fish leaving this unused portion. This material is a readily available supply for processing into fish meal.

In terms of value per unit weight, the fish meal industry processes the low value species that are not used commonly for direct consumption. In the case of the Peruvian anchoveta, a small portion of the catch is cleaned and canned, but the majority of the catch is utilized in the industrial sector. In order for these fish to be eaten directly, each fish must be cleaned and processed (Stansby 1963). Additionally, the anchovy are not the highly desired fish for human consumption. The extensive processing per weight results in little economic incentive when compared to the larger, higher value species of finfish. Fish, such as salmon, earn considerably more revenue per weight than industrial species and are more desirable for
human consumption. The characteristics of the Peruvian anchovy make it ideally suited to be reduced to fish meal.

**Principal Consumers of Fish Meal**

Fish meal is used by several industries that utilize it as an input product. It is primarily used as a protein additive to fortify animal feed in the livestock and aquaculture industries. Specifically, the poultry industry is the largest user of fish meal in the world although it is also used in other livestock feeds (Ellis 1990). Aquaculture is another primary user of fish meal which is manufactured into food pellets for feed. Fish meal is a primary ingredient in feed for fur-bearing animals such as mink. The high nutritional value of fish meal translates into high quality fur, but the fur industry has declined substantially in recent years. Secondary uses include both the pet food and fertilizer industries. Although this practice has declined, fish meal still serves as an excellent source of protein. Fish meal can also serve as a fertilizer given its high content of phosphate and nitrate. However, fish meal is not widely used as a fertilizing agent because profit margins are almost non-existent (Meade 1991). From an economic standpoint, fish meal is best used as a high value feed additive since the price received compared to other uses is relatively high.
Major Consumers of Fish Meal

<table>
<thead>
<tr>
<th>Consumer</th>
<th>% Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poultry Industry</td>
<td>60%</td>
</tr>
<tr>
<td>Pig Industry</td>
<td>20-25%</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>10%</td>
</tr>
<tr>
<td>Fur and Pet Food</td>
<td>5%</td>
</tr>
</tbody>
</table>

(Source: Starkey 1990)

Protein Percentage in Common Meals

<table>
<thead>
<tr>
<th>Protein Meal</th>
<th>Protein %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Fish Meal (anchovy)</td>
<td>65%</td>
</tr>
<tr>
<td>White Fish Meal (pollock)</td>
<td>62%</td>
</tr>
<tr>
<td>Shrimp Meal</td>
<td>51%</td>
</tr>
<tr>
<td>Meat and Bone Meal</td>
<td>47%</td>
</tr>
<tr>
<td>Soybean Meal</td>
<td>45%</td>
</tr>
<tr>
<td>Crab Meal</td>
<td>38%</td>
</tr>
</tbody>
</table>

(Source: GTA Fisheries Consultants Ltd.)

Fish Meal Percentage in Common Feeds

<table>
<thead>
<tr>
<th>Feed Type</th>
<th>Fish Meal %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy Cow (in 1990)</td>
<td>1.5 - 3.0%</td>
</tr>
<tr>
<td>Catfish (in 1986)</td>
<td>8.0 -10.0%</td>
</tr>
<tr>
<td>Catfish (in 1990)</td>
<td>4.0 - 5.0%</td>
</tr>
<tr>
<td>Poultry (in 1968)</td>
<td>12.0 -15.0%</td>
</tr>
<tr>
<td>Poultry (in 1990)</td>
<td>5.0 - 7.0%</td>
</tr>
</tbody>
</table>

(Source: Starkey 1990, Hardy and Masumoto 1990, Vondruska 1990)

Protein Requirements in Common Feeds

<table>
<thead>
<tr>
<th>Feed Type</th>
<th>Protein %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poultry</td>
<td>16-22%</td>
</tr>
<tr>
<td>Finfish</td>
<td>40%</td>
</tr>
<tr>
<td>Commercial Salmon</td>
<td>50%</td>
</tr>
<tr>
<td>Catfish</td>
<td>30-36%</td>
</tr>
<tr>
<td>Eel and Yellowtail</td>
<td>45%</td>
</tr>
<tr>
<td>Trout</td>
<td>35-44%</td>
</tr>
</tbody>
</table>

(Source: Starkey 1990, Hardy and Masumoto 1990, Vondruska 1990)
Properties and Qualities of Fish Meal

Among the various livestock and aquaculture industries, protein requirements and profiles vary. Nutritional studies have found that fish require a much greater percentage of protein in their diet compared to livestock. Typical poultry feed contains about 21 percent protein while farm-raised salmon require food with approximately 35-40 percent protein in their feed intake (GTA Fisheries Consult. Ltd 1989). To satisfy the protein requirement for their feed, poultry and pig farmers add 4-15 percent fish meal (GTA Fisheries Consult. Ltd. 1989). This percentage is far below the levels found in aquacultural feed. Obviously, the livestock industry is taking advantage of cheaper protein meals such as soybean meal. In addition, using too much fish meal in livestock feed can impart a fishy taste to the meat. Therefore, fish meal is used primarily as a fortifying agent that is rich in valuable minerals.

Fish meal is ideally suited for use as a protein-rich feed source. It is reduced from fish that are rich in protein, fats, and oil. As a result, the dried meal serves as an excellent fortifying agent with high concentrations of the amino acids lysine and methionine (GTA Fisheries Consult. Ltd 1989). The high protein percentage in fish meal leads to faster growth in the animals. It has minerals, vitamins, and polyunsaturated fatty acids that promote growth and feed conversion to animal protein (Meade 1991).
This high protein requirements in these feeds makes fish meal an attractive additive or fortifying agent in the feed industry. Small quantities can be added to supplement the diet of livestock with valuable minerals, vitamins, and protein. For many years, fish meal was included in the diets of livestock for the added growth that could be achieved with the so-called unknown growth factors (UGFs) found in fish meal (Starkey 1990).

**Classes of Fish Meal**

Generally speaking, there are three common grades, or qualities, of fish meal that are bought and sold in the world market. These are high, middle, and low quality meal. The grade depends on the protein percentage that is found in the meal. Obviously, meals with a higher percentage of protein will promote greater growth rates and sell at a premium. Lower quality fish meal is graded at less than 60 percent protein (GTA Fisheries Consult. Ltd, 1989). The lowest class of meal is processed from the lowest quality fish that contain the least protein and most bone per unit weight. As a result, the low grade of fish meal has a high ash (bone) content. A typical example of fish belonging to this class is the Gulf of Mexico or Atlantic menhaden.

Middle quality protein meal is the most common class of fish meal with a protein percentage range from 64-69 percent (Guanaye Toc. 1987). The standard protein percentage for this
class has been established at 64-65 percent and is traded on
the world market. The price that is quoted most frequently is
the cost/insurance/freight (cif) price per metric ton at
Hamburg since Germany is the largest importer of fish meal
(GTA Fisheries Consult. Ltd. 1989). The anchovy, sardine, and
pilchard all form the base of this most common middle class of
fish meal.

The middle class of fish meal can be further subdivided
into three subgroups. These include standard 65 fish meal,
high quality 68 fish meal, and prime or special fish meal
(Guanaye Toc. 1987). The standard 65 meal is largest subgroup
of the middle class of fish meal. It is made primarily from
the pilchard, anchovy, and mackerel. High quality 68 fish
meal is also processed from these species of fish, although
quality and size are improved. Greater care is involved in
the processing to achieve a minimum protein content of 68
percent. This is done with low-temperature drying instead of
flame drying and improved filtering of ash. The last subset
of the middle class of meals is the prime or special fish
meal. This subset often refers to the highest class of fish
meal. It is dried at low temperatures to maintain high levels
of protein and improve digestibility characteristics (Guanaye
Toc. 1987). Fish meal holds up well once it is hydrolysed, or
put into water, unlike many of the protein meals derived from
vegetables such as soybeans.
Middle Class Fish Meal Properties

<table>
<thead>
<tr>
<th></th>
<th>Standard 65</th>
<th>High Quality 68</th>
<th>Prime Meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>65% min</td>
<td>68% min</td>
<td>68% min</td>
</tr>
<tr>
<td>Fat</td>
<td>14% max</td>
<td>14% max</td>
<td>12% max</td>
</tr>
<tr>
<td>Moisture</td>
<td>10% max</td>
<td>10% max</td>
<td>10% max</td>
</tr>
<tr>
<td>Salt/Sand</td>
<td>7% max</td>
<td>7% max</td>
<td>5% max</td>
</tr>
<tr>
<td>Antioxidant</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
</tr>
<tr>
<td>Digestibility</td>
<td>not set</td>
<td>92% min</td>
<td>94% min</td>
</tr>
</tbody>
</table>

* data obtained from Guanaye Tocopilla Plant Figures

The last broad class of fish meal covers the highest quality which may include some of the prime or special meal of the middle class. It contains more than 70 percent protein and has the lowest ash content between 10 and 12 percent) (GTA Fisheries Consult. Ltd. 1989). This best grade of fish meal is used primarily in the aquaculture and fur sectors. All the forms of fish meal are treated with antioxidant to eliminate salmonella and pathogenic microorganisms. Clearly, fish meal with its high content of nutrients could be subject to spoilage and pathogens if it is not treated. Additionally, fish meal must be kept dry to prevent spoilage and decay. Fish that are caught by the industrial fisheries must be processed shortly after being caught or otherwise preserved (Meade 1991). If the fish are not handled properly, they begin to deteriorate and lose protein content (GTA Fisheries Consult. Ltd 1989). As indicated in the previous table, the highest quality fish meal has the greatest amount of protein and protein digestibility.
Protein Meal Prices

The world price of fish meal is related to the total supply of protein meals that are available. Given the different percentages of protein that are present in the various types of protein meal, price is a reflection of both the protein content and total supply. As soybean meal has a lower percentage of protein, its price is much lower per ton than fish meal. Soybean meal accounts for approximately 60-75 percent of the total world protein market (GTA Fisheries Consult. Ltd. 1989, Crowder 1990). World production of soybean meal continues to climb displacing the demand for other protein meals including fish meal. The price movements of the different sources of protein meal are highly correlated and significant. The coefficient of determination is significant well beyond the 99th percent confidence interval. Correlation among various sources of protein meal appear on the page below:

Regression Analysis between Protein Meals

Time Period: 1965-1990 (monthly avg. values)

Coefficients of Determination

<table>
<thead>
<tr>
<th>Coefficients of Determination</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard fish meal 65 to Menhaden meal</td>
<td>0.83</td>
</tr>
<tr>
<td>Standard fish meal 65 to Anchovy meal</td>
<td>0.80</td>
</tr>
<tr>
<td>Standard fish meal 65 to Soybean meal</td>
<td>0.69</td>
</tr>
<tr>
<td>Menhaden Meal to Soybean meal</td>
<td>0.77</td>
</tr>
</tbody>
</table>

* Price series data obtained from U.S. Dept. of Commerce, NOAA, NMFS.
The correlation between the various protein meals appears to be directly related to the amount of protein. The highest correlation exists between standard fish meal 65, anchovy meal, and menhaden meal. Although standard fish meal usually contains a higher percent of protein compared to menhaden meal, this difference is minimal and the two commodities are common substitutes. However, there is a notable difference when comparing the various types of fish meal with lower protein percentage soybean meal. The highest correlation is between soybean meal and menhaden meal. Since menhaden meal belongs to the lower grade class of fish meals, it is not surprising that the price better reflects the price of soybean meal.

The high alpha levels of confidence demonstrate the correlation of price volatility between the various protein meals. In addition, there is a fairly constant price ratio of 1.85-2.20 : 1 between fish meal and soybean meal (Starkey 1990). This ratio has remained fairly consistent through time since 1965 with changes occurring during El Niño and unusual harvests of soybeans. The occurrence of El Niño in the Pacific reduces the South American catch which is used to produce about one third of the world's yearly production (Idyll 1973). About half of the world's yearly exports originate in South America (Data obtained from USDA database). The ratio is also influenced by the yearly harvest of soybeans. Since the U.S. accounts for about one half of the
world's soybean harvest, the U.S. crop condition can greatly influence supply and resulting protein meal prices (Connell Commodities, Co. 1990). The close relationship between the two commodities allows a certain degree of price forecasting as well as cross-commodity hedging.

In terms of price elasticity, fish meal is rather inelastic (-0.7), however, compared to other protein meals, it is one of the most elastic (Crowder 1990). This implies that users can not switch easily from one protein meal source to another. The aquaculture industry is not very capable of switching to alternate protein sources, such as soybean meal, since this product does not hold up well in water. Thus, substitutes are available, but switching presents certain complications for given industries.

Major Fish Meal Producers

World production of fish meal was 6.67 million metric tons (mmt) in 1990 compared to 4.8 mmt in 1980 (Ellis, 1990). Production of fish meal is extremely concentrated in the South American market. Chilean production of fish meal rose by 23 percent between 1988 and 1989, compared to an average world rate of 3 percent (Hardy and Masumoto 1990). In 1990, Chile was the world's largest fish meal producer with Peru a close second (Data obtained from USDA yearly fish meal statistics). South American production accounts for approximately one third of the total world production. Given this statistic, the
Figure 5: Major fish meal producing nations - The Devastating effect of El Niño can be seen in the data series in early 1970's (Source: data courtesy of USDA)
enormous impact of El Niño on the price and availability of fish meal is apparent. The Soviet Union and Japan are the next two largest producers with a combined production that continues to grow. These two nations account for about 30 percent of the fish meal market. Japanese production is especially interesting since it has grown rapidly throughout the 1980's. Their annual catch of Japanese Sardine in the northern Pacific has increased dramatically in the last few years (Data obtained from FAO Fisheries Yearbook). Despite these changes, South America will continue to supply a great portion of the world's fish meal in the immediate future.

Since 1968, world production of soybean meal has increased by over 176 percent. During the same period, fish meal has only increased by 27 percent (Starkey 1990). Industry experts expect soybean meal production to continue to increase while fish meal production is projected to decrease. Although fish meal experienced a smaller growth in production, consumption of fish meal increased by over 40 percent from 1977 to 1986 (GTA Fisheries Consult. Ltd. 1989). Livestock offals and waste also provided a greater source of protein meal in the U.S. during the 1980's. As consumer tastes became more health conscious, the beef industry responded by offering leaner cuts of meat. An indirect result of providing leaner meats has been greater wastes, trimmings, and fat associated with marginal meat. These wastes can be effectively utilized by the protein meal consumers.
Competition in the protein meal market may also increase with the introduction of synthetic proteins in coming years. Although not widely used today in the feed industry, experts believe that production of these synthetic amino acids will increase fourfold during the next three years (Starky 1990). The cost of production of these proteins still outweighs any value that can be added in the livestock or aquaculture business. However, expanding production and improving technology may reduce costs. It could become "easy to replace 100 pounds of soy meal with 3 pounds of lysine and 97 pounds of corn meal" (Starkey, 1990). Although growth in these other sectors of the protein meal market has exceeded fish meal production, net demand for fish meal continues to increase since overall consumption continues to increase.

Future Demand for Fish Meal

The aquaculture sector appears to be a growing area of demand for fish meal in the world market. Aquaculture operations, as mentioned previously, need better quality feed with higher percentages of protein. Fish meal has the high content of protein that is necessary to achieve appropriate growth rates in cultivated species. The fish protein that is found in the fish meal is assimilated more easily by fish in aquacultural settings. "Aquaculturists use fish meal because it fills protein needs and because high-quality fish meals are well utilized by the fish compared with cheaper plant or
animal protein" (Starkey 1990). However, these facilities need high protein qualities as well as meals that are low in ash content.

The high ash content of fish meal poses another problem for aquacultural use of this feed. Although ash is an excellent source of minerals, only a small percent is needed to serve as a fortifying agent. Greater percentages are wasted resulting in runoff that is high in excess nutrients. This can lead to serious pollution concerns and localized phytoplankton blooms such as the occurrence of Red Tide. Screening fish meal can reduce the ash content and improve the product quality, but this imparts higher costs of production (Hardy and Masumoto 1990). The use of ice to better preserve the product also prevents the decaying process in which valuable protein content is lost before the fish is processed (Meade 1991). This presents additional costs to the fish meal industry, especially South American producers such as Peru, which has not traditionally used any ice (Kilpatrick 1990). However, using higher quality meals can result in improved growth rates and weight gain in fish raised in captivity (Hardy and Masumoto 1990).

If one views the past development and growth of the aquaculture industry, it is clear that the industry will continue to expand. The dramatic rise in aquaculture production in Norway, China, and other nations will result in increased demand for fish meal. Since this demand is
relatively inelastic, the sector could become an important source of demand in the future. One future opportunity is the growing aquaculture industry in Asia. Shrimp farms and mariculture operations have increased substantially. The Chinese eel, or baby eel, market is an excellent example of a potential demand. Operators are willing to pay a premium for high quality fish meal which constitutes about 70 percent of the young eel diet (Burnham et al 1990). Growth in the aquaculture industry can only serve to increase the demand for fish meal. In terms of commercial aquaculture, shrimp farming represents the largest share of fish meal use followed by the salmon industry (Kilpatrick 1990). The high-value aquacultural sector uses the most fish meal. Currently, only 10 percent of the world's supply of fish meal is utilized in commercial aquaculture, but that figure is expected to rise to 20 percent by the year 2000 (Kilpatrick 1990).

### Fish Meal Use in Commercial Aquaculture in 1992

<table>
<thead>
<tr>
<th></th>
<th>Shrimp</th>
<th>Eel</th>
<th>Salmon</th>
<th>Marine Species</th>
<th>Trout</th>
<th>Catfish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36%</td>
<td>12%</td>
<td>28%</td>
<td>6%</td>
<td>15%</td>
<td>3%</td>
</tr>
</tbody>
</table>

(Source: Kilpatrick 1990)

As mentioned previously, the poultry industry consumes the largest amount of fish meal. The enormous growth of the poultry industry in the U.S. that occurred throughout the last decade has increased the demand for fish meal. It is highly
likely that the poultry industry will continue to grow in the future. Fish meal producers can be assured of consumer demand as long as their prices remain competitive with alternate protein meal sources. The pet food industry represents another area of steady demand for fish meal that will probably increase. Recent studies have also demonstrated that use of fish meal in the dairy industry can increase milk production (Starkey 1990). The amount of milk production actually increased in cows that consumed feed with a small content of fish meal. Thus, the unique nutritional value of fish meal may increase its attractiveness to additional consumers.

The future of the fish meal market will depend on the industry's ability to cope with increasing competition in the protein meal market. Producers must market fish meal in the industries that require high percentages of protein. Obviously, production of soybeans and research in synthetic proteins and amino acids will continue to increase competition. However, this increase is likely to compete with the lower quality fish meals first. Unfortunately, fish meal producers will not be able to compete with the lower prices offered by soybean growers. As a result, fish meal producers should concentrate production efforts in the higher quality market.

If fish meal producers want to increase production of higher quality meals, they must improve processing. Although low temperature drying and rapid conversion may increase
protein percentages in meals making them more attractive to consumers, these practices will also result in increased costs. Therefore, the fish meal market will revolve around the producer's economic ability to improve product quality while stabilizing costs. If demand for high quality fish meal increases, this will further encourage producers to improve processing.
CHAPTER III

METHODOLOGY

Linear Regression in Fisheries

The primary hypothesis is to test whether sea-surface temperature data may be utilized in a statistical model to help explain variations in fish catch, fish meal production, and fish meal prices. In order to accomplish this objective, it is necessary to choose a statistical test that will establish a correlation between the relevant variables. Previous fisheries studies that tested for a correlation between fisheries production and environmental variables have used linear regression as the statistical test (Mendelssohn and Cury 1987, Muck et al. 1989, Bohle-Carbonell 1989, Guillen and Calienes 1981, Mendelssohn and Mendo 1987, Austin and Ingham 1979). The use of linear regression enables the researcher to establish a correlation between an independent variable, or variables, and a dependent variable (Bohle-Carbonell 1989). Additionally, it tests for linear relationships between variables that may serve as a forecast tool or model.

The ability to forecast is contingent upon the certainty that the independent variable, or variables, are known in advance. If these variables can be determined before the
dependent variable is known, then this dependent variable may be forecast with a given degree of confidence and variance. Basically, the linear regression model tests the fit of a regression line through a scatter-plot of the two variables on the x-axis and the y-axis. The regression line is the line running through the data points that minimizes the squared distances, or deviations, of the points and the line (Blalock 1979). Thus, it is best-fitting line between the two variables and the test determines whether the relationship is statistically significant. Linear regression can plot X as a function of Y, or Y as a function of X (Ricker 1973). This thesis will run regression models using the program 'Quattro Pro' to establish whether a correlation exists between the independent and dependent variables. It will plot Y (fish catch, or the dependent variable) as a function of X (SST, or the independent variable). This test will lay the foundation for a subsequent bioeconomic model. Obviously, the stronger the linear relationship between the two variables, the greater the degree of correlation and forecastability. So, the regression model serves as a forecast tool enabling an estimate based on incomplete information.

**Testing the Hypothesis**

In testing for a correlation between sea-surface temperature and anchovy catch in the Peruvian upwelling ecosystem, the hypothesis has an implicit direction. Since El
Niño dramatically impacts the ecosystem and reduces the anchoveta stock, a rise in the sea-surface temperature would be expected to be consistent with a reduction in overall fish catch, a reduction in the production of fish meal from the anchovy, and a subsequent rise in the fish meal price as a result of shorter supply. Although fisheries production and landings are more than just a function of SST, this thesis is attempting to determine the contribution of SST, or the importance SST plays in modelling landings. Similar studies using regression and correlation have made similar links between pelagic fisheries production and SST (Muck 1989, Csirke 1989, Guillen and Calienes 1981, Mendelssohn 1989, Mendelssohn and Mendo 1989, Muck et al. 1989). As a consequence, the hypothesis is one-tailed in nature and the direction has been implied.

Warmer SST will be consistent with an ENSO signal and this should lead to lower landings of anchovies. Although catchability coefficients have been shown to increase at first during an El Niño for the anchovy, this is usually a short-run effect and overall landings throughout an El Niño year will eventually decline (Csirke 1989). The analysis will also test for time lags since the rise in SST will occur before any decline in the catch of anchovy and production of fish meal. Thus the methodology looks at the correlation of the same concurrent 12 months of values between the independent and dependent data series as well as the impact of the previous
year of independent data. Thus, it considers a one year lag effect of the independent series on the following year of the dependent data.

After establishing correlations between SST and landings of anchoveta, the study progresses with a second test establishing a correlation between anchovy landings and fish meal production. Since SST is the initial variable used to forecast anchovy landings, using landings to forecast fish meal production carries an implicit SST weight or contribution to the next step. Since the majority of the catch is used as a primary input into the fish meal industry, the correlation is expected to be highly significant. Having established a correlation between landings and fish meal production, the thesis will lastly concentrate on developing a statistical model to forecast the price of fish meal.

Developing a forecast model for the price of fish meal presents an increased level of complications in that the price of fish meal is a function of several variables. Additionally, it is not possible to include all of the variables that impact the price of fish meal. Consequently, three key variables are used given their relevance in influencing the price of fish meal. These variables are the price of soybean meal, which is a close protein substitute that dominates the world's protein meal market, the production of Peruvian fish meal, and sea-surface temperature. The use of key variables in statistical analysis, while discounting
other less important variables is consistent with past studies (Mendelssohn 1989). Ideally, it would be desirable to include all relevant variables, but realistic constraints require that certain variables not be included. As a result, variables that are more trivial, or unattainable, have been left out of the correlation analysis.

Given the importance that soybean plays in the world market for protein meal, it is imperative to include the cost of soybean in the regression model. The production of Peruvian fish meal is used since the price of fish meal will clearly be a function of the availability or supply of the product. Sea-surface temperature is used in the multi-variate regression analysis to determine if it may be used as a harbinger, or lead signal, for future price increases. If SST is related to the price of fish meal, then rises in the temperature in the ocean may serve as signal that prices are going to increase. This thesis tests the correlation between the price of fish meal and these variables.

Potential Biases

In using correlation, there are a number of important potential important biases that must be addressed. First and foremost, there must be a logical and rational reason behind the statistical model. Rather than just generating correlation coefficients between different combinations of the same data set in the hope of getting a statistically
significant result, the researcher should explore the functional relationships between the variables and then pursue the most likely relationships. If the former methodology is utilized, no plausible cause and effect explanation may be advanced since "correlation does not necessarily indicate causality" (Austin and Ingham 1979, Vondruska 1981). In this way, the correlation is reinforced conceptually and the possibility of generating a spurious relationship is minimized.

Another important potential bias is the accuracy of the data used in the study. Obviously, the legitimacy of a forecast model is contingent upon the validity of the data. Even the raw data may contain a margin of error as most sampling techniques are subject to both random and non-random errors. Unfortunately, potential errors in the raw data series can not be corrected since they were collected by outside sources. These errors are especially problematic with the historical data since sampling methods were less advanced compared to current standards. This may result in some degree of sampling bias. This should not impact the validity or significance of the results (Ricker 1973).

The analysis of the thesis uses monthly averaged values for SST, landings, fish meal production, soybean meal price, and fish meal price. Frequently, reliable fisheries data is difficult to obtain whether in the United States or elsewhere. Sometimes the data is not even available (Mendelssohn 1989).
Although the SST database and price series are complete up to 1990, anchovy landings and Peruvian fish meal data ends in the early 1980's. Attempts were made to obtain the most current data, but only total yearly landings and meal production were available. Since the study makes use of monthly averaged values, the yearly data is not included in the statistical analysis.

One last potential data bias is the practice of underreporting the Peruvian anchovy catches. Official figures may be lower than the actual amount of anchovy landed due to losses at sea, losses during unloading of the catch, losses incurred at the processing plants, and intentional underreporting of real quantities landed (Castillo and Mendo 1987). During the height of the fishery, figures suggest that underreporting totalled approximately 12 percent of the total catch (Castillo and Mendo 1987). These figures may have been as high as 20 to 30 percent in certain years (Castillo and Mendo 1987). Once again, it is impossible to check the validity of the raw data, but it is assumed that the underreported catches are randomized over the entire period under investigation.
Despite the vast amount of subject material available on oceanography, economics, and climatology, few studies have linked all of these fields. Principles of economics seem misplaced among scientific studies dealing with biological, physical, and chemical ocean processes. This study requires an interdisciplinary approach in order to develop relationships and models. The analysis is based on monthly averaged values for SST, anchovy landings, Peruvian fish meal production, fish meal prices, and soybean meal prices. The use of monthly averaged values enables the research to determine which months are the most important in terms of the correlation between SST and fisheries landings. Monthly averaged values are frequently used in analyzing SST data (Slutz et al. 1985, Brainard and McLain 1987, Muck et al. 1989). Monthly data also provides more observations which, in turn, represents a generous degree of freedom for the statistical analysis. Obviously this is desired as larger sample sizes are more consistent with the universal population.
Sea-Surface Temperature Data

The SST data was obtained from the Comprehensive Ocean Atmosphere Data Set release 1 (Slutz et al. 1985). This series provides historical SST on a global coverage based on either 2° or 10° resolution. The data has been collected for the period of 1900 to 1982 (Slutz et al. 1985). The difference in resolution is provided to meet different research needs. Obviously, the 2° data may be used to study smaller marine systems that require finer resolution. This study will use the 10° data since no catch data is available for smaller areas. It consists of monthly averages of SST based on ship-track observation and SST buoy measurement.

The major flaw with this data set rests with the older historical data. There are brief periods in which no ship observation recorded the SST in a given location. This has occurred in the past when travel by sea was less frequent (Slutz et al. 1985). Major changes have taken place during this century (Reynolds 1987). Additionally, there are gaps in the data corresponding to the two World War periods when national security prevented continuation of scientific research (Slutz et al. 1985). The method used to take SST measurements has changed over time with advances in technology. Sea-surface temperature is now recorded by the intake of sea water through the engine, replacing the older method of bucket observation (Reynolds 1987). Engine intake observation imparts a positive 0.5° C anomaly which must
Figure 6: COADS 10° sea-surface temperature boxes
(Source: Slutz et al. 1985)
be corrected for when using the observations in conjunction with an older series (Reynolds 1987, Slutz et al. 1985). Most of these potential biases present problems in the COADS SST source prior to 1950 and almost all errors or inconsistencies have been corrected for since that time. This thesis uses the most recent data since 1950.

In order to complete the SST series through 1990, a second data set is used to fill in the years from 1982 to 1990. This data was obtained through the Climate Analysis Center (CAC) (Reynolds 1991). It also uses monthly averaged values of SST based on either a 2° or 10° resolution, but its source differs slightly. The CAC SST series is comprised of both AVHRR satellite pass data and ship track SST measurements. Thus, it is a blended series using both in situ ship track and buoy observations and satellite measurements (Reynolds 1988). The ship track and buoy observations employ the same measurement techniques as the COADS series, but the CAC blended data supplements these observations with satellite pass data to improve the coverage. The Advanced Very High Resolution Radiometer (AVHRR) satellite observations can induce a degree of bias since cloud coverage, atmospheric disturbance from volcanoes, nighttime bias, and transmission complications can skew the actual SST value (Reynolds 1989). Satellite measurement also only observes SST in the first few millimeters (mm) of the ocean surface compared to ship and buoy observation down to a depth of few meters (Reynolds
Figure 7: A sample isotherm map (Source: Reynolds 1989)
1988). However, the blended series has been corrected for any biases. It has also been shown to be the most accurate and conservative measurement of SST out of all the sampling techniques (Reynolds et al. 1987). The SST series is completed by the use of the CAC blended data.

The 10° resolution data was used by aggregating boxes into predefined oceanic regions or larger boxes. Specifically, four larger regions were defined and form the spatial regions of the study. These four oceanic regions move from east to west across the equatorial Pacific from the coast of Peru to approximately the middle of the equatorial Pacific. These boxes, termed Niño 1, Niño 2, Niño 3, and Niño 4, are the principal regions monitored by the Climate Analysis Center for the development of El Niño (Toole 1984). The box closest to the coast of Peru, Niño 2 (0-10°S, 270-280°E), is consistent with most of the fishing area for the Peruvian anchovy. Niño 1 (0-10°N, 270-280°E) corresponds to the area just north of this box. Both regions just off the coast of South America are 10°x10° represent the smallest of the four larger boxes in question. Niño 3 (10°S-10°N, 210-270°E) and Niño 4 (10°S-10°N, 160-210°E) represent larger ocean regions across the equatorial Pacific that experience significant warming during an El Niño. Given the larger sizes of these latter two boxes, their SST serves as a more consistent indicator and signal of warm anomalies.
Figure 8: Aggregated large sea-surface temperature boxes. The Niño boxes lie off the coast of Peru, S.A.
Figure 9: SST anomalies in degrees Celsius in Niño boxes showing El Niños in 1982-83 and 1987 (Source: data from COADS)
**Additional Data**

All of the Additional data that is required for the statistical analysis was acquired through the National Marine Fisheries Service (NMFS) under the National Oceanic and Atmospheric Administration (NOAA). This includes the anchovy landings, Peruvian fish meal production, fish meal prices, and soybean prices. All of the data represents monthly averaged values that are obtained from the NMFS DBFISH (database fish) computer database. Despite the accessibility to historical data on the NMFS database, current fisheries data related to Peru is more difficult to obtain. All of the series obtained could not be updated to 1990 from the NMFS database for the study so they were supplemented by the following sources. The price series data was completed using records obtained from the United States Department of Agriculture (USDA). Additionally, these price series were adjusted for inflation using the annual summary report for agricultural prices published by the Department of the Interior. Anchovy landings were updated through 1984 using the data obtained from the International Center for Living Aquatic Resources Management (ICLARM) records (Tsukayama and Palomares 1987). No additional source could be located to update figures on the monthly production of Peruvian fish meal, as only yearly data is frequently published (FAO Fisheries Yearbooks). As a result the data series of monthly production of Peruvian fish meal is the only limiting data in the study.
Data and Model

Preliminary analysis of the relevant series was complicated by two characteristics of the data. First, the data itself is drastically skewed so that statistical analysis proved difficult. Since the data is monthly averaged values for anchovy landings, Peruvian fish meal production, SST, and protein meal prices, the sample sizes were large containing as many as 310 observations. However, the variance between the values of landings, as well as fish meal production, were enormous. Landings could reach values over 1 mmt for 1 month or bottom out near 0 for another month. Thus, the data was not normally distributed. The range gives an idea of the variable nature of the upwelling ecosystem of Peru in terms of environmental conditions and biomass.

The second problem that created a hurdle for the quantitative analysis of the Peruvian anchovy is the huge change in the ecosystem that occurred in the early 1970's. As a result of overfishing and the strong El Niño of 1972, the anchovetaa essentially collapsed and created a shock through the entire ecosystem. The guanobird population declined and other species took off possible occupying part of the niche originally held by the anchovy. The relative percentage held by each of the species began to change dramatically after this collapse. As a result, the biomass profile has been extremely dynamic over the last few decades (Muck et al. 1989). To overcome the effect of this collapse and dramatic change in
the ecosystem, the analysis stratifies the data series into
two subgroups. One set consists of data prior to but
including 1970 while the other data set is made up of post
1970 information. This solution solves the problems that are
mentioned above.

The Physical Bioeconomic Model

In order to correlate sea-surface temperature with
anchovy landings, fish meal production, and fish meal price,
a logical sequence of relationships is developed to describe
the process. First, an attempt is made to correlate SST with
landings of anchovy. Although fisheries production and growth
is more than just a function of SST (ie. predation, nutrients,
mortality, recruitment, etc.), the purpose of this step in the
conceptual model is to determine the contribution of SST to a
forecast model for anchovy landings. As a result, all
additional variables are discounted or excluded from the
correlation analysis. Each of the four aggregated SST boxes,
Niño 1, Niño 2, Niño 3, and Niño 4, were tested for
correlation with landings in the consecutive year as well as
a one year lag prior to the next year's landings in Niño 2.
All of the months within this two year period, including the
same year and the year prior, are tested for possible
correlation with landings. Thus, the first step establishes
the first necessary correlation between SST and anchovy
landings for the reduction to fish meal.
After the first step, the physical bioeconomic model progresses with a test for correlation between landings and Peruvian fish meal. Most of the catch is directly utilized in the industrial sector for the production of fish meal, so the correlation is expected to be quite high. All other influences on the production of Peruvian fish meal, such as world demand and supply, are not factored into this step. Since freshly caught anchovies are an extremely perishable commodity, the test for a time lag is limited to the months in the same year of landings as compared to meal production. This second tier of the bioeconomic model provides the linkage between landings and fish meal production.

The last step of the conceptual model attempts to forecast the price of fish meal. This correlation is expected to present the greatest complications in that fish meal price is a function of several important variables such as supply, demand, imports, exports, prices of substitutes, and market conditions. The sheer number of potential variables would make the inclusion of all of these variables nearly impossible. Therefore, three key variables have been chosen to be considered in this study. They are soybean meal price, Peruvian fish meal production, and a lagged SST variable. All other market variables and influences have been exclude from the analysis. The last step finishes the relationship between SST and fish meal price and provides a forecast model for the actual price of fish meal.
LANDINGS = L
MEAL PRODUCTION = M
FISH MEAL PRICE = F, SOY MEAL PRICE = S

\[ L_t = f \left( SST_{t-n}, \text{Other Factors} \right) \]
\[ M_t = f \left( L_t, \text{Market Factors} \right) \]
\[ F_t = f \left( S_t, M_t, SST_{t-n}, \text{Market Conditions} \right) \]
\[ L_t = f \left( SST_{t-n} \right) \]
\[ M_t = f \left( L_t \right) \]
\[ F_t = f \left( S_t, M_t, SST_{t-n} \right) \]

Figure 10: Physical bioeconomic model showing formulas
Figure 11: Physical bioeconomic model depicted graphically as a flow diagram
Sea-Surface Temperature and Landings

The first step of the correlation analysis provides the basis, or foundation, of the bioeconomic model. As was initially expected in the original hypothesis, higher SST in each of the larger oceanic boxes involved in the study were consistent with an El Niño signal and lower landings of anchovy. As described in the methodology, sea-surface temperature for each of the predefined boxes was correlated with monthly landings of anchovy. All of the boxes reflected a similar relationship in that higher SST experienced mostly during El Niño years are consistent with lower landings of anchovy in the pre 1970 data. Unfortunately, this relationship seems to fall apart in the two data series after 1970. The following section will present the findings of the analysis of the boxes.

Analysis of Niño 1 and Landings

Niño 1 is the SST box that lies just to the north of the main anchoveta region (MAR) overlapping most of the anchovy range. After testing for correlation between the two monthly data series, it was determined that March SST anomalies had the most impact on October and November landings of anchovy. To test the relationship and smooth the results, an October-November average landings figure (dependent variable) was regressed with the preceding March SST anomalies. Looking at landings prior to 1970, the regression analysis resulted in a
coefficient of determination \( (r^2) \) of 0.63 with 14 degrees of freedom (df). This is statistically significant at the 0.05 confidence interval and the research hypothesis is accepted. Thus, some 63 percent of the variance between March SST anomalies and average October-November landings is explained by SST. This result is encouraging since it reinforces the original research hypothesis.

Another interesting result is the fact that most of the lower values of landings correspond to El Niño years. That is, low landings were experienced in years with above average SST anomalies. In searching for a rational explanation for the relationship between March SST anomalies and average October-November landings, several observations can be made. March SST, as mentioned in the literature review, is the month in which classical El Niño warming is the greatest (Harrison and Cane 1984). Its impact on the anchovy can be pronounced since the bulk of landings at this time of the year is made up of young, juvenile fish, or peladilla, which are ready for recruitment (Paulik 1981). If warmer SST has a negative impact on the survival of young fish about to reach sexual maturity and recruitment into the fishery, warmer March SST anomalies would be expected to be consistent with lower landings later in the year. This may be especially pronounced during the next major spawning period in the year which would take place during September, October, and November (Muck 1989). This period will depend on mortality of the anchovy.
Figure 12: Analysis of SST anomalies in Niño 1 and anchovy landings from 1956-1970 - the inverse relationship between SST and landings can be seen
Figure 13: Estimate of anchovy landings based on SST in Niño 1 - the forecast model works well for the data prior to 1970 and the collapse of the anchoveta
population in the months proceeding the spawn. The regression analysis is consistent with this as the average October-November landings are experienced later in years with larger March anomalies.

Using the slope of the regression line and the constant (y-intercept), it is possible to build a forecast model of average October-November landings from the observed March SST anomaly. The forecast model is fairly accurate in forecasting landings up to 1970. After that year and the collapse of the anchoveta, the forecast model estimate deviates from the actual landings. Although the estimate indicates the direction, either up or down, its value is very different from the real landings. Thus, the forecast model works well on the data series prior to 1970. The collapse may be explained by the shift of species in the ecosystem that occurred after the collapse of the anchoveta.

Analysis of Niño 2 and Landings

Niño 2 is the SST box that directly overlaps the MAR and the distribution of the main populations of anchovies. Following the same procedure for the first box, monthly SST anomalies were regressed with the same monthly landings data series prior to 1970. A similar relationship was discovered in that the average March SST anomaly was related to average July-August landings of anchovy. The analysis generated an \( r^2 = 0.64 \) with 12 degrees of freedom which is statistically
significant at the 0.05 alpha level. As mentioned previously, the development of El Niño experiences the greatest degree of warming during March (Harrison and Cane 1984). This is the initial month of onset of the El Niño and the month in which young recruits dominate the populations of anchovies.

Survival of these young fish will determine the strength of the next major spawn and future numbers of anchovies. July and August are the height of the Austral winter and are also the months that usually experience the greatest amount of upwelling. Catches in these months tends to be the lowest since the upwelling is strong. The strong upwelling brings sufficient nutrients but they are dispersed over a wider range along with the populations of anchovies making them harder to catch. If there is an adverse affect on the mortality of the young recruits then future populations of anchovy will be smaller. Consequently, the populations will be even more dispersed in July and August and landings should be smaller. The regression analysis reinforces this hypothesis since above average March SST anomalies are followed by lower average July-August landings. Thus, March SST is a precursor, or lead indicator, of landings the following July and August. Once again, the lowest average landings are experienced in years of El Niño and the warmest SST anomalies.

A forecast model may be constructed once again from the slope of the regression line and the constant. The forecast model is fairly accurate with the data series prior to 1965.
Figure 14: Analysis of SST anomalies in Niño 2 and anchovy landings from 1957-1970 - the inverse relationship between SST and landings is apparent
Figure 15: Estimate of anchovy landings based on SST in Niño 2 - the forecast model works until vedas, or closed seasons are instituted
instead of 1970. Although this lead to some initial criticism of the division of the complete data series into pre and post 1970 categories, further investigation determined that 1966 marked the first year that closed seasons, or vedas, were first initiated. This represents an external variable that was not included in the regression analysis as information regarding the vedas, or closed seasons could not be obtained. This may account for the deviation of the estimate from the actual value. While the estimate is close prior to 1965, the relationship falls apart in later years.

**Analysis of Niño 4 and Landings**

The regression analysis between SST and landings was done between monthly average SST anomalies in Niño 4 and monthly average landings of anchovy. Niño 4 represents the largest of the aggregated SST boxes and it is located farthest from the Peruvian coastline out in the middle of the equatorial Pacific. It also experiences the smallest variations, or anomalies, in SST since it is the largest and does not experience upwelling. Thus, it serves as the most conservative El Niño indicator. After testing the two data series, another relationship was determined in which warmer SST anomalies were consistent with lower landings of anchovies. Although the result is not statistically significant, it does reinforce the findings of the first two regression runs.
Figure 16: Analysis of SST anomalies in Niño 4 and anchovy landings from 1953-1970 - Once again, the inverse relationship is seen.
Figure 17: Estimate of anchovy landings based on SST in Niño 4 - although the forecast is not as accurate, the relationship falls apart after 1970
The regression analysis found that June SST anomalies were correlated with average July-August landings of anchovy. This correlation generated an $r^2 = 0.50$ with 13 degrees of freedom. Although the result is not significant, the negative slope of the regression line is consistent with the inverse relationship between SST and landings. El Niño years were again found with the values of lower landings and warmer SST anomalies. As is done with the first two runs, a forecast model can be constructed from the slope of the regression line using the independent variable to estimate the landings, or dependent variable. The findings for Niño 3 were the same as they were for Niño 4.

**Analysis of Landings and Fish Meal Production**

The relationship between landings and fish meal production represents the second step in the bioeconomic model. It was hypothesized that the correlation between landings and Peruvian fish meal production would be high as most of the catch is used by the industrial sector. To test the relationship, the average monthly landings series was regressed with the average monthly production of fish meal. Unfortunately, monthly fish meal production figures could not be obtained beyond 1979. However, given that the data is monthly, the sample size was extensive containing a total of 180 observations. This is more than sufficient to run the regression analysis.
Figure 18: Analysis and relationship between anchovy landings and Peruvian production of fish meal - The relationship is almost perfectly linear
A correlation coefficient computed between the two variables yielded a coefficient of determination of $r^2 = 0.95$. There were 178 degrees of freedom and the correlation was statistically significant well beyond the 0.01 confidence interval. Since most of the catch is used for processing fish meal, the high correlation was not surprising. Some 95 percent of the variance between the 2 series can be explained by landings of anchovy. Although the regression analysis considered a time lag, the best fit resulted when no lag was used. Since the anchovy must be processed quickly before decomposition, no time lag is required.

The high correlation can be translated into an accurate forecast model provided landings are known with some degree of certainty. Landings will serve as an indicator of the unknown fish meal production. The regression line equation may be used to generate an estimate of fish meal production using landings and this forecast will be almost certain. Since SST anomalies were used in the initial step to forecast the landings of Peruvian anchovy, landings in the second tier of the model indirectly reflect SST anomalies in their values.

Analysis of Fish Meal Price

In order to analyze the fish meal and soybean meal price series, they were first corrected for inflation and a base year was chosen. The series were adjusted using the Producer Pricing Index (PPI) for prices received by farmers for all
Figure 19: A time series of unadjusted protein meal prices
Figure 20: A time series of protein meal prices adjusted for inflation
ADJUSTED PROTEIN MEAL PRICES
SOYBEAN MEAL $ vs. FISH MEAL $

Figure 21: Analysis and relationship between soybean meal and fish meal prices
FORECAST ANALYSIS
FISH MEAL ESTIMATE

Figure 22: Estimate of fish meal price based on known soybean meal prices
agricultural products and 1990 was chosen as the base year since most of the data series ended in 1990. If regression is used to test the correlation between just the monthly average price of soybean meal, the independent variable, and the monthly average price of fish meal, the dependent variable, different results are generated depending on the adjustment for inflation. Unadjusted, the regression analysis generates a $r^2=0.83$ with 310 degrees of freedom since monthly data is available from 1965 through 1990. Adjusted for inflation, the regression analysis generates a $r^2=0.67$ with 310 degrees of freedom. Despite the difference, both results are statistically significant well beyond the 0.01 confidence interval. Since soybean meal captures the vast majority of the world's protein meal market, the price of soybean meal is probably one of the most important determinants of the price of fish meal. Thus, a forecast model can be constructed as before using the equation of the regression line with the slope and the constant. Although this estimate is fairly accurate, the model may be improved by including more variables such as fish meal production and the lagged SST variable.

Obviously, the price of fish meal will be a function of the price of the major source of protein meal, soybean meal, and the availability or supply of fish meal. In addition, a 1 year lagged SST variable was included since a plot of lagged SST and fish meal price seemed to move together. If SST is
Figure 23: A plot of SST anomalies in Niño 1 and actual fish meal prices
Figure 24: A plot of -1 year lagged SST anomalies in Niño 1 and actual fish meal prices
related to the price of fish meal and it rises before the price of fish meal, then SST may be used as a lead indicator that fish meal prices are going to increase. Since monthly Peruvian fish meal production figures are only available from 1965 through 1979, the sample size is limited to 180 observations, but this is more than sufficient for the regression analysis.

Using just the monthly average price of soybean meal as the independent variable and fish meal price as the dependent variable (both adjusted for inflation), the regression analysis generated an $r^2 = 0.67$ with 178 degrees of freedom. This coefficient of determination is the same as when the entire data series is used from 1965 through 1990. When Peruvian fish meal production is included as an additional independent variable for multi-variate analysis, the coefficient of determination improves to $r^2 = 0.68$ with 177 degrees of freedom. In the last step, all 3 variables (-1 year SST, Peruvian fish meal production, and soybean meal price) were used and the regression analysis improved once again with an $r^2 = 0.72$ and 176 degrees of freedom. The equation of the regression line was:

$$ y = \alpha + \beta x \quad \text{(Blalock 1978)} $$

Equation 1:

Fish Meal $\$ = 64.34119(-1 \text{ yr SST}) - 0.00022(\text{Meal Prod.})$

$$ + 1.55444(\text{Soybean Meal } \$) + 147.0821 \quad 102 $$
Fish Meal $ = 64.34119(-1 \text{ yr SST}) - 0.00022(\text{Meal Prod.})
\begin{align*}
(14.13902) & \quad (0.0000752) \\
+ 1.55444(\text{Soybean Meal $}) + 147.0821 \\
(0.090282) & \quad \text{(Constant)}
\end{align*}

The standard errors of the coefficients appear in parentheses below the actual equation. The standard error of the $Y$ estimate was 97.82734.

This was used to generate an estimate of fish meal price from the forecast model. It serves as a more accurate forecast of fish meal price than using just soybean meal or soybean meal price and fish meal production. The correlation improved as additional variables were included in the multi-variate regression analysis as was expected.

Unfortunately, the fish meal production figure were not up-to-date and the regression analysis did not cover the most recent data. Both SST and soybean meal prices were available from 1965-1990 so the last portion of the analysis focused on using these two variables which were available up to 1990 to forecast fish meal price. Using just soybean meal price as a forecast variable for fish meal price, an $r^2=0.67$ with 310 degrees of freedom was computed. Once the -1 year lagged SST was included as an independent variable, the relationship improved to $r^2=0.69$ with 309 degrees of freedom. Both of these results are highly significant beyond the 0.01 confidence interval. The equation for the regression line is:

Equation 2:

\begin{align*}
\text{Fish Meal $} &= 38.82213(-1 \text{ yr SST}) + 1.676629(\text{Soy Meal $}) \\
& \quad + 94.59327
\end{align*}
Fish Meal $ = 38.82213(-1 \text{ yr SST}) + 1.676629(\text{Soy Meal $})$
\begin{align*}
(7.59049) & \quad (0.065888) \\
+ 94.59327 & \\
\text{(Constant)} & 
\end{align*}

The standard errors of the coefficients appear in parentheses below the actual equation. The standard error of the $Y$ estimate was 83.75717.

This relationship would likely improve if current monthly Peruvian fish meal production could be included. However, the degree of improvement is unknown given the fact that Peruvian fish meal plays a less important role in the world protein meal market. Since the collapse of the Peruvian anchoveta, Peru's contribution in terms of fish meal has declined substantially. Additionally, soybean meal has taken off and now dominates world protein meal usage. As a result, Peruvian anchovy accounts for a lower percentage of the total protein meal market. Thus, including Peruvian fish meal production figures in a bioeconomic model to forecast the price of fish meal is less important today than in previous years.
Figure 25: An estimate of fish meal prices based on -1 year lagged SST, fish meal production, and soybean meal price up to 1979

FORECAST ANALYSIS
FISH MEAL ESTIMATE

R-SQUARED 0.72 df=178
ALL VARIABLES INCLUDED

ACTUAL FORECAST
FORECAST ANALYSIS
FISH MEAL ESTIMATE

Figure 26: An estimate of fish meal prices based on -1 year lagged SST and soybean meal price
CHAPTER V
CONCLUSIONS

Summary of the Results

Looking at the results from each of the 3 steps of the complete bioeconomic model, a number of observations can be made. The first step computing the correlation between SST and landings exhibited the smallest coefficient, while the second step between landings and fish meal production had the highest correlation. Fisheries production is more than just a function of SST, but this environmental variable may be included in an analysis of the fishery. Certainly other environmental variables impact the anchoveta. These include mortality, recruitment, predation, effort, etc., and should be incorporated into a comprehensive fisheries production model. The vast amount of data that is required complicates the scientific study and management of fisheries such as the Peruvian anchoveta. In fact, including every variable would not be feasible. Despite this, the statistically significant correlation ($\alpha=0.05$) indicates that SST may be used as a useful forecasting variable in the anchovy fisheries model. In two of the regression runs between SST and landings, SST explained over 60 percent of the variance of landings prior to
1970. The results of this thesis are better than those of other studies which found SST to explain 43 percent of the variance of pelagic fisheries production, or 55 percent excluding 2 outliers (Mendelssohn and Cury 1987). The analysis of this thesis has discovered a correlation between SST and anchovy catch which accounts for more than 60 percent of the variance. These results are encouraging given the large number of variables that influence fisheries in the Peruvian upwelling ecosystem. The order of magnitude of the correlation is similar to a study which found the biomass of anchovy highly dependent on the availability of food (in terms of primary productivity of Chlorophyll a (Guillen et al. 1981). Therefore, the research hypothesis may be accepted supporting a statistically significant relationship between SST and landings, fish meal production, and fish meal prices.

The second step of the physical bioeconomic model was also successful in that a high correlation was found between anchovy catch and Peruvian fish meal production. Although this correlation was expected to be highly significant, this step is an essential element in the overall model. The physical bioeconomic model follows rationally so that the correlations may be explained and interpreted in a logical manner. As mentioned previously, this minimizes the possibility that the results are spurious. Therefore, the correlation between anchovy landings and Peruvian fish meal production provides the linkage between SST and fish meal prices.
The final step in the physical bioeconomic model provides a forecast model for the price of fish meal. The correlation analysis produced correlation coefficients that were highly significant in each of the different runs. The three independent variables included in the analysis, soybean meal price, Peruvian fish meal production, and a one-year lagged SST, generated a regression equation that may be used to forecast the price of fish meal. Although current data relating to monthly Peruvian fish meal production was not available, both the price series and SST data were available up to 1990. Using the regression equation derived from fish meal price and soybean meal price, the estimate had a mean absolute standard error (MASE) of 12.98 percent. Given that the standard deviation of the price of fish meal adjusted for inflation is $151.50, this error range is both acceptable and supports the validity of the model. A mean absolute standard error of 12.98 percent corresponds to a range of $62.90 compared to the natural variability or variance of fish meal prices which is more than double this range.

Using the regression equation with both soybean meal price and lagged SST, a forecast estimate was generated with a mean absolute standard error of only 12.20 percent. Thus, the estimate improves when the lagged SST variable is included in the equation for the fish meal price estimate. This mean absolute standard error translates into an average range of $59.12 which is again less than the one standard deviation
range of $151.50. Unfortunately, monthly Peruvian fish meal production figures were not available to generate a current estimate based on the three variables. However, the estimate model based on just soybean meal price and lagged SST did forecast with a mean absolute standard error of 12.20 percent which is fairly accurate.

To further validate the results of the thesis, an out-of-sample test was run with the data from January, 1991 through July, 1992 to test the forecast model's accuracy. Using just soybean meal price as a forecast variable, the mean absolute standard error of estimated fish meal price was 25.1 percent. The inclusion of one-year lagged SST into the forecast model, as in equation 2, dramatically improved the estimate closer to the actual value. The mean absolute standard error decreased substantially to 5.5 percent which provides further support for the initial results and the original hypothesis of the thesis.

In terms of making a correct buying decision, direction may be viewed as a more important factor than the degree of the oscillation (Starkey 1990). Basically, one needs to know whether prices are going to increase or decrease in order to make a proper buying or selling decision. Since an El Niño includes a number of distinct sequential phases, the onset may be monitored and forecast with a fair degree of accuracy (Glantz 1984). Once an El Niño is forecast, steps may be taken to make the appropriate buying and selling decisions.
given the likely impact the event has on marine resources. Thus, the monitoring of SST may become a useful management and economic tool. The net effect may tend to reduce price perturbations over time.

**Discussion and Recommendations**

In order to meet the new challenges posed by rapid development in the fishing industry, fisheries management has attempted to deal with the problems of conservation and overfishing. Obviously, it is desirable to maintain fish stocks at abundant healthy levels and to avoid destructive harvesting of fish stocks. Successful management of fisheries should be able to maintain stocks near their optimum levels and yield. This promotes maximum efficiency and minimum costs to the industry. Unfortunately, fisheries management often arrives after the damage of overfishing has been incurred as the case of the Peruvian anchoveta. In addition, management is often plagued by self-motivated interests rather than a true objective concern for conservation. Immediate economic concerns can draw attention away from prudent fishing policies. As a result, fisheries management must face the double-edged sword with conservation on one side and profitability on the other.

Fisheries management is confronted by the additional challenge of natural oscillations in the marine environment. The event known as El Niño causes drastic changes in both the
physical and biochemical marine environment, especially in the Pacific (Cane 1983). The warm waters associated with the event can disrupt the natural food chain and abundance of nutrients (Idyll 1973). Scientists are just beginning to appreciate the enormous impact El Niño has on a global scale. In terms of fisheries management, it is crucial that one understands the mechanics and results of these events in order to prevent these natural disruptions. If management is to succeed, managers must be able to adjust population and catch quotas depending upon environmental conditions.

Warmer SST serves as a harbinger for the El Niño and the adverse effects it brings. Frequently, species on a lower trophic level react more rapidly to environmental changes compared to those organisms that are located higher in the food chain (Austin and Ingham 1979). The anchovy is definitely a lower trophic fish. Thus, including SST as a variable in a bioeconomic model to forecast the landings of pelagic species would draw attention of fisheries scientists and managers to changes and potential threats in the marine environment. This may provide valuable response time to the fisheries and fisheries management. Examples of management techniques that might be useful include catch quotas, gear restrictions, and closed seasons. Consequently a natural buffer may be provided as a result and analysis of SST may serve to conserve fish populations and to avoid potential disaster.
Sea-surface temperature may also be used to further exploitation of certain pelagic species that congregate and migrate along specific isotherms (Harris 1989). Activities of fishing fleets may be assisted through the use of SST analysis and catches and profits may increase as effort declines. While this may improve economic conditions and profitability in the fishing sector, it may also lead to declines in fish stocks. Fisheries managers must appreciate and consider these potential results to avoid collapse. As a result, SST analysis may serve to improve fisheries management or destroy the fisheries resources. It clearly depends on the nature of the use and the aims of the policy makers.

Conclusions

Healthy development of a resource involves wise management in order to maintain that resource at abundant levels and to avoid overexploitation. The upwelling ecosystem of Peru once supported an anchovy fishery that provided 38 percent of the world's fish meal (Sorensen 1983). The FAO Stock Assessment Panel determined that the fishery could sustain a catch of 9.5 mmt under proper management. This catch could be processed to 2 mmt of fish meal for animal feed (IMARPE 1981). Unfortunately, proper management did not reach the fishery before the damage was done. The natural oscillation known as El Niño seems to have extenuated the collapse of the fishery which occurred in the early 1970's.
Although the fishery once supplied five percent of the Peruvian Gross National Product (GNP), stock populations have been reduced far below previous levels (Glantz 1981). Once a fishery has been reduced to such low levels, it is doubtful whether populations will ever be able to recover assuming continued levels of fishing pressures. Fishing activities would have to be almost completely curtailed in order to rebuild future recruitment.

We are just beginning to understand the full impact of our development upon the environment. Additionally, natural changes or oscillations in the oceans still lie beyond the control of resource management. Full employment of a resource in light of environmental uncertainty such as El Niño points to a potential hazard for that industry. The case of Peruvian fisheries demonstrates the need to consider all the parameters involved with a given industry. Long term management is crucial if that renewable resource is to remain at optimum levels. Policy must be guided from an objective stance considering the most beneficial regulations and conservation measures. This will ensure the future of the industry and the availability of the resource on which it depends.
APPENDIX A

Acronyms and Terminology

Anomaly: A positive or negative deviation from the mean expected value. For the purposes of this thesis it is assumed that the deviation is in degrees Celsius.
AVHRR: Advanced Very High Resolution Radiometer
Bochilera: Spanish term for an anchovy purse seiner
CAC: Climate Analysis Center
Catchability Coefficient: unit of measurement of ease of capture of some amount of fish with a given level of effort.
CIF: Cost Insurance Freight
COADS: Comprehensive Ocean-Atmosphere Data Series release 1
Convection: Atmospheric process of evaporation and heat transfer associated with warm SST.
CPUE: Catch Per Unit Effort
df: degrees of freedom used in correlation
El Niño: A warm SST event in the western Pacific associated with climatic changes.
ENSO: El Niño/Southern Oscillation
FAO: Food and Agriculture Organization
Fish meal: a ground dried fish and fish waste used as fertilizer and animal food.
g C/m²/day: grams of carbon fixed per meter square/yr
ICLARM: International Center for Aquatic Resources Management
Isotherm: A line of constant SST.
La Niña: A cold SST event in the western Pacific
MAR: Main Anchoveta Region
MASE: Mean Absolute Standard Error
NMFS: National Marine Fisheries Service
MMT: million metric ton
MSY: Maximum Sustainable Yield
NOAA: National Oceanic and Atmospheric Association
Peladilla: Spanish term for a young, juvenile anchovy
Pelagic: relating to or occurring in the open ocean surface.
PESCA\PERU: The nationalized anchoveta industry of Peru formed in 1968.
PPI: Producer Pricing Index
PPM: part per million
PPT: part per thousand
SOI: Southern Oscillation Index
SST: Sea Surface Temperature observation in degrees Celsius.

TAC: Total Allowable Catch of Fish
Thermocline: boundary between warm surface ocean water and colder, nutrient-rich deeper water
UGF: Unknown Growth Factors attributed to fish meal
UN: United Nations
USDA: United States Department of Agriculture
USDOI: United States Department of the Interior
Veda: Spanish term for a closed season of fishing
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