A GEOGRAPHIC ANALYSIS OF TRENDS IN CATCH, CATCH PER UNIT OF EFFORT (CPUE) AND VALUE OF BIGEYE TUNA (THUNNUS OBESUS) BY THE HAWAI‘I LONGLINE FISHERY FROM 1994 – 2008

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF ARTS

IN

GEOGRAPHY

December 2011

By

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ACKNOWLEDGEMENTS

This thesis would not have been possible without the data provided by the NOAA Pacific Islands Fisheries Science Center. I would like to express my deepest gratitude to the personnel at PIFSC, including, but not limited to, Sam Pooley, David Hamm, Kimberly Lowe and Russell Ito for their guidance and willingness to advise me at all stages of this project.
ABSTRACT

Bigeye tuna (*Thunnus obesus*) is the cornerstone of Hawaii’s deep-set, commercial longline fishery and fishers have been willing to travel farther from Hawaii in search of it. This study serves as an introduction to Hawaii’s longline fishery and some of the challenges it continues to face. The commercial tuna fishery in Hawaii has many players: the fishers trying to make a living, the government organizations working to manage our ocean resources sustainably, the people with an appetite for fish, and the people who say that not enough is being done to protect these apex predators. This study approaches this resource management issue by utilizing a geographic information system to display and describe the spatial-temporal patterns of Hawaii’s longline fishery from 1994 to 2008 and demonstrates that this fishery has grown in every regard. There has been a steady increase in effort, catch and value of bigeye tuna. There has also been a growing geographic distribution of the fishery, however the vast majority of bigeye catch and value occurred around the main Hawaiian Islands. The catch rate has not shown the same steady increases and that leaves fisheries managers in the position to make the difficult decisions needed to ensure a sustainable fishery.
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<tbody>
<tr>
<td>CPUE</td>
<td>Catch per unit of effort</td>
</tr>
<tr>
<td>DAR</td>
<td>Department of Aquatic Resources</td>
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<tr>
<td>DLNR</td>
<td>Department of Land and Natural Resources</td>
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<tr>
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<td>Exclusive Economic Zone</td>
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<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<td>ESA</td>
<td>Endangered Species Act</td>
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<td>FAD</td>
<td>Fish Aggregating Device</td>
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<td>IATTC</td>
<td>Inter-American Tropical Tuna Commission</td>
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<td>MBTA</td>
<td>Migratory Bird Treaty Act</td>
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<td>Marine Dealer Reporting System</td>
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<td>Magnuson-Stevens Fishery Conservation and Management Act</td>
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<tr>
<td>MSY</td>
<td>Maximum Sustainable Yield</td>
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<tr>
<td>mt</td>
<td>Metric Tons</td>
</tr>
<tr>
<td>nm</td>
<td>Nautical Miles</td>
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<tr>
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<td>Pacific Island Fisheries Science Center</td>
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<td>Regional Fishery Management Organizations</td>
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<td>RCV</td>
<td>Robust Coefficient of Variation</td>
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<tr>
<td>UFA</td>
<td>United Fishing Agency</td>
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<tr>
<td>WCFFC</td>
<td>Western and Central Pacific Fisheries Commission</td>
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<td>WPRFMC</td>
<td>Western Pacific Regional Fishery Management Council</td>
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CHAPTER 1. INTRODUCTION AND BACKGROUND

This study examines the geographic distribution of catch rates and catch per unit of effort (CPUE) of bigeye tuna (Thunnus obesus) by Hawaii’s commercial longline fishery from 1994 to 2008, and the economic value from 2000 to 2008. It will answer the questions: what large-scale spatial and temporal trends have occurred in the Hawaii longline tuna fishery and how do they relate to distance from Hawaii? Being a geographic study, it is concerned with how people interact with space, and will serve as an introductory story of Hawaii’s commercial longline fishery. Background information on bigeye tuna and Hawaii’s longline tuna fishery will help provide context for some of the issues the fishery has faced during its growth in the last fifteen years. Some of the issues faced by the fishery include the health of the pelagic environment, the economic success of the fishers, fishers' interactions with protected marine life, consumers’ growing desire to eat fish, and the challenges faced by fishery managers who must take all these things into consideration. That will set the backdrop for an examination of how the longline fishery has changed geographically through time and what effect distance from Hawaii has on the success of commercial longline fishers.

One of the tools used to help accomplish this is a geographic information system (GIS), which aids in the analysis and display of fisheries data. However, before a GIS could be utilized, data sets from different sources had to be integrated. By providing some understanding of the large-scale spatial and temporal trends that have occurred in the fishery, it is my hope that this study will make a contribution to help ensure that Hawaii’s longline tuna fishery operates sustainably for many years to come.
1.1 Global to Local Perspective

Tuna are an increasing part of the world’s diet, especially since the 1940s and 1950s when industrial fishing gained momentum (Block and Stevens 2001; Miyake et al. 2004). Strong market demand has made tuna the main source of income for many fishers around the world and demand for tuna has shown no signs of waning. Levels of catch for major tuna species in 2007 were more than 4 million metric tons around the world and have increased about 9% since 2001 (FAO 2009). This study focuses on bigeye tuna because, of the major tuna species, bigeye tuna make up a major component of the catch by fishers around the world.

The majority of the world’s bigeye tuna supply comes from the Pacific Ocean, about 66% of the total world catch (FAO 2009). Bigeye tuna are the economic cornerstone of the tropical longline fishery in the western and central Pacific Ocean (Langley et al. 2004). Prices paid for both frozen and fresh bigeye tuna on the Japanese sashimi market are the highest of all the tropical tunas. Japan and Taiwan are the largest harvesters of bigeye tuna, followed by the United States (Agro Products 2008; FAO 2009). Bigeye tuna landings by all U.S. fisheries in 2008 amounted to 10,523 mt, a decrease of just under 5% from 2007 (Pritchard 2009).

Locally, bigeye tuna are the economic cornerstone of the Hawaii-based commercial longline fishery. In 2008, bigeye accounted for 30% of the number of fish caught by the Hawaii longline fishery and about 58% of its revenue (NMFS 2009). This catch was down from 2007, when bigeye accounted for 46% of the number of fish caught. In 2008, bigeye tuna landings in Hawaii added up to 6,078 mt and were worth
almost $50 million (NMFS 2009). While the total mass of bigeye caught in 2008 was less than in 2007, the value of the fishery increased by about $9 million.

It is clear that the pressure on fish stocks is continuing to increase around the world and throughout the Pacific. Also, concerns of overfishing, where the level of fishing mortality jeopardizes the capacity of a fish stock to produce the maximum sustainable yield (MSY) on a continuing basis, are now being realized for three major tuna stocks, bigeye, yellowfin (*Thunnus albacares*) and Pacific bluefin (*Thunnus orientalis*). Enacting the most effective plans to best manage our highly valued marine resources has been an ongoing struggle, and this information has caused the debate to intensify.

The importance of these fish cannot be overstated. Bigeye tuna play a major role in the ocean environment as apex predators, and as a source for food and income around the world and in Hawaii. It is imperative that policy makers design and implement the most informed and effective fishery management policies to help ensure that we can continue to rely on our marine resources.

### 1.2 Bigeye Tuna

Bigeye tuna (Figure 1.1) occur worldwide in the tropical and subtropical waters of the Atlantic, Indian and Pacific oceans and are considered highly-migratory. Figure 1.2 shows their global distribution. They are relatively fast growing, and have a maximum recorded fork length of about 2 m (Harley et al. 2009). The optimum water temperature for bigeye tuna lies between 17°C and 22°C (Hanamoto 1987). However, Brill et al. (2005) state that bigeye tuna regularly expose themselves to temperatures of 25°C at the
surface and 5°C. Interestingly, unlike most other fish, tuna are warm blooded. They have a complex temperature regulation system and a high metabolic rate, which allows them to maintain their body temperature above that of the surrounding water (IATTC 1988).

Bigeye are not normally found in waters with dissolved oxygen less than 1 ml/l and occur, generally, from the surface down to about 500 m, depending on their size (Hanamoto 1987). Larger bigeye have been known to occur even deeper (Hanamoto 1987; Musyl et al. 2003; Evans et al. 2008). Archival tagging of bigeye tuna has revealed that some adults dive as deep as 815 m (Musyl et al. 2003), and Schaefer and Fuller (2002) recorded some bigeye tuna that exceeded depths of 1,000 m. Tagging studies also show that they spend about 90% of their time at night between the surface and 50 m, then descend at dawn, following their prey, which consist of a variety of fish species, cephalopods and crustaceans. Larger bigeye tuna are also known to occasionally eat smaller, younger bigeye tuna (Schaefer and Fuller 2002). These are apex predators that feed during both day and night (Evans et al. 2008).

Bigeye tuna swim constantly to pass large amounts of oxygen through their gills for metabolism. They must also swim continuously because once they grow large enough to become heavier than the surrounding water they would sink. Their unique physiology allows them to travel very long distances and display extraordinary bursts of speed. They have well streamlined bodies and a lunate, or crescent shape, tail which allows for maximum forward thrust and high hydrodynamic efficiency (IATTC 1988).

Bigeye are believed to spawn through the year in tropical regions, specifically between 10° N and 10° S, and during the summer at higher latitudes (Collette and Nauen 1983). Spawning occurs primarily at night and reproductively active females spawn about
every 1.3 days (Schaefer et al. 2005). They are capable of releasing millions of eggs, of which very few reach maturity. These are a very interesting and unique fish, of which, much more remains to be learned.

1.3 Longline Fishing in Hawaii

One of the primary methods used to supply bigeye tuna to Pacific nations and abroad is longline fishing. After the development of on-board, super-cold storage, the longline fishery gradually changed its target from yellowfin and albacore (*Thunnus alalunga*) for canning to bigeye for sashimi (Miyake et al. 2004). Currently, the longline fishery is Hawaii’s largest commercial fishery in terms of landings and economic value (WPRFMC 2008). Hawaii-based longline fishers travel great distances in search of swordfish (*Xiphias gladius*), but most of the vessels targeting tuna tend to operate close to the island chain or on seamounts a short distance outside the longline closed zones or bordering the Hawaii exclusive economic zone (EEZ) (Curran et al. 1996).

When the Hawaiian Tuna Packers Ltd. cannery closed in 1984, only 15 longline vessels were fishing out of Hawaii. There was a rapid increase in fleet size during the late 1980’s, and by 1993, the Hawaii fleet had exceeded 150 vessels and continued to increase rapidly (Pooley 1993). In 1994, Hawaii’s longline fishery was capped at 164 vessels, partially in response to the growing pressure on tuna stocks (WPRFMC 2004). The number of active vessels in the Hawaii longline fleet fluctuates, but has been reasonably stable over the past several years (Figure 1.3). Both in 2007 and 2008, there were 129 active vessels and in 2009 there were 125 (NMFS 2008). Commercial longline vessels are generally classified according to their length. The maximum vessel length allowed in
Hawaii is 30 m, although the average size is usually between 19 and 21 m (WPRFMC 2009).

Longline fishers in Hawaii catch a variety of species of tuna and billfish. Swordfish and bigeye tuna are the two major species targeted by the Hawaii longline fleet (Sharma and Leung 1999). However, fishers in Hawaii catch yellowfin, albacore and skipjack (*Katsuwonus pelamis*) tuna. They catch two other billfish species with shallow-sets, blue marlin (*Makaira nigricans*) and striped marlin (*Tetrapturus audax*). They also catch a variety of other pelagic species, including opah or moonfish (*Lampris guttatus*), mahi mahi or dolphinfish (*Coryphaena hippurus*) and wahoo (*Acanthocybium solandri*). These other species, along with a few others, are considered incidental catch, meaning that while they are not targeted species, they have a market value that makes them worth their space in the hull, so fishers can expect to make a profit from them.

Longline fishing consists of setting a long mainline with branch lines, usually about 3 m long, extending from the main line. A mainline must exceed 1.6 km in length to be considered a longline. From 1995 through 2008, the average mainline length deployed by a Hawaii longliner was 48.2 km, with a maximum of 629 km in 2004 (NMFS 2008). One baited hook is attached to the end of each branch line. The branch lines, with their baited hooks attached, are placed between surface floats and are commonly baited with scad, sanma, squid, sardine or herring (NMFS 2006).

The target species determines the number of hooks placed between floats and the depth of the hooks. Longline fishers in Hawaii target both swordfish and tuna. When targeting swordfish, they place an average of four to five hooks between floats and the hooks are set relatively shallow, usually between 20 to 30 m in depth. For tuna, fishers
place 20 to 40 hooks, closer together. Floats are widely spaced, allowing the hooks to drop much lower in the water column, between 100 to 400 m in depth (Figure 1.4). A study by Bigelow et al. (2005) showed that out of 266 sets, the median depth of the deepest hook was 248 m. Of all the sets deployed by Hawaii longliners that were logged from 1994 to 2008, 87% were deep-set.

Longliners targeting swordfish usually set their gear at dusk and haul it at dawn, while those targeting tuna commonly deploy their gear in the early morning and leave it to soak for an average of 12 hrs. During which time, the line moves with the currents. A radio transponder at each end of the mainline allows the vessel captain to find the line when it is ready to haul. For a relatively long mainline, it may take almost 24 hrs from the beginning of the deployment of the mainline to the end its retrieval. Longline vessels deploy an average of 10 to 16 sets per trip.

Size, mass, quality and market demand determine the price for which a fish sells. There are a couple circumstances that can reduce the overall quality of a fish’s meat. First, the amount of time a fish spent on the hook may affect its quality. A fish that was hooked near where the line was set will stay in the water longer than a fish that was hooked near where the set ended, as the line is normally hauled in from where the set ended. So, for a long mainline, a fish can stay on a hook for many hours, leaving it exposed to possibly warmer temperatures and predators that take advantage of a fish carcass. Second, a fish’s quality can be reduced by how much time it spends in the vessel’s hull. A fish hauled in on a set deployed earlier in a fishing trip will remain in the vessel’s hull longer than a fish hauled in during the last set deployed; this becomes a factor considering longline trips can last for as long as a couple of weeks. Another factor
influencing the value of a particular fish is the market price of tuna at the time it is sold. The annual average price of bigeye fluctuates, but has mostly increased since 2002 (Figure 1.5). The greatest increase during the period of the study occurred in 1999, and, most recently, the second greatest increase occurred in 2008, which set the highest average price per pound at $3.71.

1.4 Fisheries Management in Hawaii

The commercial pelagic longline fishery in Hawaii is managed through a Fishery Ecosystem Plan (FEP) developed by the Western Pacific Regional Fishery Management Council (WPRFMC) and approved by the National Oceanic and Atmospheric Administration (NOAA) under the authority of the Magnuson-Stevens Fishery Conservation and Management Act (MSA). The U.S. is also a member of two international fishery commissions that monitor fishing on the high seas of the Pacific Ocean, the Inter-American Tropical Tuna Commission (IATTC) and more recently, since 2004, the Western and Central Pacific Fisheries Commission (WCPFC). These are two of eleven multi-lateral Regional Fisheries Management Organizations (RFMO) that collect, analyze and share relevant fisheries data around the world.

The convention area for the IATTC is the eastern tropical Pacific Ocean between the coast of the Americas and 150° W longitude and from 40° N to 40° S latitudes. Sixteen member countries are party to the treaty and there are seven other cooperating non-member nations that make up the IATTC. The WCPFC’s convention area is the area of the Pacific west of 150° W longitude, but there is some overlap of convention areas (Figure 1.6). The WCPFC is made up of twenty-six member nations, eight participating
territories and seven cooperating non-members. They work with one another by sharing pertinent fisheries catch data and also work closely with the United Nations Food and Agriculture Organization (FAO) in order to avoid duplication of collection and processing effort for scientific data related to fishing in the Pacific.

These two RFMOs work towards ensuring the long-term sustainable harvest of highly migratory fish stocks in the Pacific. They determine harvest limits and enact other management measures to prevent over-fishing and to promote viable fisheries. If the U.S. commercial fishery reaches the catch limit for a particular species set by a RFMO, NOAA closes that fishery for the remainder of the calendar year. For example, in July 2006, after the 500 metric ton limit for the eastern tropical Pacific was reached, NOAA closed the U.S. longline fishery for bigeye tuna in the IATTC convention area through the year (71 FR 38297). This also happened in December 2009 in the western Pacific, when the Hawaii longline fishery was closed for the last three days of the calendar year, after it was determined that fishers would reach the quota of 3,763 metric tons of bigeye tuna set by the WCPFC (Star Bulletin 2009). Fortunately for the fishers, it was only for the last three days of the year, but it demonstrates that the quotas set by the RFMOs are being reached and that they are of great importance because they can have very real economic impacts on the fishers.

While those RFMOs focus on fishing in the high seas, the WPRFMC, or the Council, is the policy-making agency responsible for monitoring and managing fishing activity inside of the U.S. EEZ, extending from 4.8 to 322 km offshore (Figure 1.7). The Council is one of the eight fishery management councils created in the U.S. by the MSA. The Council works closely with RFMOs and it is critical that the Council have their
support, because fisheries under the Council’s jurisdiction comprise less than 5% of bigeye tuna catch in the Pacific Ocean. For some perspective on which management areas in the Pacific experienced the most fishing during the period of the study as it pertains to the Council, the Hawaii longline fleet caught 46.6% of its catch outside of the U.S. EEZ, and 34.5% inside the main Hawaiian Islands EEZ (Figure 1.8). It is the Council that is responsible for making sure that fishery management plans (FMP) comply with the MSA, which was enacted in 1976, then amended in 1996.

Hawaii’s Department of Land and Natural Resources (DLNR) has charged its Division of Aquatic Resources (DAR) with managing fishing in state waters, which extend from the shore to 4.8 km offshore. Commercial fishermen are required to report their landings to DAR. DAR also performs marine life and habitat surveys, creel and port surveys, fish market sampling and other scientific surveys to monitor and assess the condition of Hawaii’s inshore and coastal resources. Commercial fishing landing data have been collected, processed and compiled by DAR since 1948. These data are used by state and federal fisheries agencies to assist in assessment and management of Hawaii’s fisheries.

1.5 Management Issues in the Pacific and the Hawaii Longline Fishery

One of the major issues faced by the commercial fisheries in the Pacific Ocean is over-fishing. One situation in which a species can be considered over-fished is when its biomass has declined to a level that jeopardizes the capacity of a stock to be harvested on a continuing basis. The IATTC recently concluded that the eastern Pacific tuna stock is probably over exploited. This multi-species stock is estimated to be experiencing over-
fishing, though is not yet in the condition defined as over-fished (IATTC 2009). Also, in 2008, the WCPFC’s Scientific Committee concluded that it is likely that bigeye tuna is in, at least, a slightly over-fished state, or will be in the near future (WCPFC 2008).

Because of this current situation, many of the management decisions made by RFMOs have been criticized by groups who complain that they are short-sighted and that the RFMOs are unable to enforce the cooperation of their members. RFMOs are also criticized for not taking strong enough measures to curb over-fishing. At its conference in Busan, South Korea in December 2008, the WCPFC reduced catch limits by 10% per year for each of the next 3 years, as opposed to the recommended 30% cut all at once. The WCPFC set the catch limits for bigeye tuna in the western and central Pacific Ocean for 2009, 2010 and 2011 at 3,763 mt, but does not include bigeye landed in American Samoa, Guam, the Commonwealth of the Northern Mariana Islands or east of 150° W. The most recent measures were reviewed in 2010 and will possibly be toughened if scientific evidence supports it.

The WCPFC is criticized by groups for not taking the advice of their own scientists at times. Even some fishery scientists complain about the lack of effective management decisions. Langley et al. (2009) state that declarations and resolutions calling for restraint in the expansion of fishing effort were largely unheeded over the last decade and, to date, the WCPFC has been unable to introduce any measures to effectively reduce, or limit, the level of fishing mortality of yellowfin and bigeye tuna. They also argue that Pacific Island nations need to collectively take the lead to ensure the effective management of this highly valued resource.
As reported by the Honolulu Advertiser on September 3, 2009, scientists working for the WCPFC found that recent measures to reduce fishing capacity were undermined by numerous territorial exemptions from catch limits. Some member nations have become good at finding loop-holes in the policy decisions or have simply been taking advantage of the fact that these RFMOs have little enforcement capability. These are only a sample of the many concerns faced by the world’s RFMOs in their effort to manage fisheries around the world.

By-catch is another management issue the commercial longline fishery in Hawaii has had to deal with, via the fishing process itself. By-catch includes a variety of sharks and other pelagic species for which the market value does not justify the space they take up in the hull. By-catch is discarded back into the ocean injured or dead. Sharks make up the largest component of by-catch, particularly the blue shark (*Prionace glauca*).

A major concern in the fishery is interactions with sea birds, marine mammals and other protected species. Species protected under the Endangered Species Act (ESA) occur throughout the region, and include seven species of marine mammals, five species of sea turtles, and one species of seabird. The species of marine mammals and seabirds occurring in the region are protected under the Marine Mammal Protection Act (MMPA) or the U.S. Migratory Bird Treaty Act (MBTA) (PIRO 2004). Of the 356 longline trips in 2009 with NOAA observers on board, there were reportedly 18 interactions with sea turtles, 19 with marine mammals, and 156 with seabirds (PIRO 2010) (Figure 1.9).

Interactions with sea turtles and marine mammals have remained below 40 for each year since 2004, but seabird interactions have had a couple of high years, with a new maximum in 2009 of 156. Albatrosses, gulls and fulmars are the seabirds most frequently
caught by longliners in the north Pacific (Brothers et al. 1999). According to these authors, the most critical threat to albatrosses and large petrels is mortality by longline vessels. In the last several years, several measures, side-setting, night-setting and using thawed, blue-dyed bait, have been introduced to help mitigate interaction with seabirds.

Sea turtles on the endangered species list also experience injury or mortality from interaction with longline gear. It is predominantly the shallow-set fishery that has interactions with sea turtles and marine mammals. For this reason, since 2006, the shallow-set fishery is restricted in its effort whenever interactions with sea turtles reach a certain level. The maximum annual limit on sea turtle interactions for the Hawaii shallow-set longline fleet is 16 leatherback sea turtles (*Dermochelys coriacea*) and 46 loggerhead sea turtles (*Caretta caretta*) (HLA 2009). The limit on loggerhead sea turtles was recently increased from 17. If either limit is reached, the shallow-set fishery is closed for the remainder of the calendar year. This has only happened in March 2006.

Measures have also been implemented to reduce sea turtle by-catch. These include the requirement of the use of barbless, circle hooks in combination with mackerel type bait. Gilman and Kobayashi (2007) found that the use of circle hooks and mackerel-type bait by the Hawaii-based shallow-set fishery reduced the sea turtle interaction rate by approximately 90% for loggerheads, 85% for leatherbacks and 89% for combined species, compared to 1994 – 2001, when the fishery was operating without such gear. They also found that there were no significant reductions in catch levels.
1.6 Marine Protected Areas

Through the years, policy makers have enacted spatial restrictions on the fishery as management measures to help protect the marine environment. For instance, in 1992, the Council established the Main Hawaiian Islands Longline Fishing Prohibited Area (57 FR 7661). This area is closed to longline fishing for the entire year and an extension of that area is closed from February 1 to September 30 (Figure 1.10). The year round closure comprises an area of 248,631 km² and the extension adds an additional 65,179 km². The Council established this closure area in an effort to reduce the interactions of longline and small-vessel troll and hand line gear, reduce fishing gear interactions with protected species and to reduce the possibility of localized overfishing.

The same year, longline fishing was also prohibited within 92.6 km of the northwestern Hawaiian Islands in order to reduce interaction with the Hawaiian Monk Seal. This area was later designated as the Papahanaumokuakea Marine National Monument by President George W. Bush in June 2006. Then, in January 2009, President Bush established the Pacific Remote Islands Marine National Monument under the authority of the Antiquities Act of 1906, designating approximately 139,833 km² as off-limits to commercial fishing. This monument is comprised of Johnston Atoll, Howland and Baker Islands, Jarvis Island, Kingman Reef and Palmyra Atoll, and Wake Island. The U.S. Fish and Wildlife Service is charged with the management of the area from the mean low water line seaward 22.2 km and NOAA manages the area from there to the border of the monument 92.6 km from the shore.
1.7 Summary

The immense amount of time and resources that go into monitoring and managing marine resources, such as bigeye tuna, reflect their importance to our society, as well as to marine ecosystems. Because our ocean resources are depended on by so many people around the world, there are concerns and complaints expressed by a wide variety of interest groups about every level of fisheries management in the U.S. and around the world. The RFMO's task to enact effective FMPs is formidable and the stakes are very high. It is crucial that they take every measure possible to ensure that the world is able to rely on its ocean’s resources for as long as possible. It is also critical that fishing nations provide up-to-date fisheries data to policy makers so that they can set appropriate catch limits and design and implement the most effective FMPs and even more important that member nations abide by the decisions made by RFMOs.

This background chapter has introduced aspects of Hawaii’s commercial longline fishery, from describing the fish and fishing methods, to a survey of the regulatory institutional landscape and some of the concerns fisheries managers must address. This study is intended as a contribution to fisheries research to help ensure that the Hawaii-based longline tuna fishery is a sustainable and viable industry. As stewards of the ocean, it is necessary to collect and begin to understand all the relevant data that will help make that happen.
CHAPTER 2. LITERATURE REVIEW

The literature regarding commercial fishery dynamics and stock assessment in the world’s oceans is substantial, stemming back to the early 1920s and 1950s’ actuarial approach, which was based on size distribution, catch rates and other readily visible population census parameters. More recently, an ecosystem-based approach to fisheries management has become a worldwide research and management priority and a government mandate for U.S. fisheries. This approach takes into account the relationship between a species and its supporting ecosystem and aims to conserve the structure and function of the marine ecosystem, in addition to conserving marine resources. A marine ecosystem, according to Matsuda and Katsukawa (2002), can be characterized by (i) temporal fluctuations, (ii) uncertainty in assessment and ecosystem processes, and (iii) an open system concerned with straddling stocks and international fisheries management.

2.1 Ecosystem Knowledge

Much of the research on bigeye tuna has incorporated oceanic parameters, such as water temperature at the surface, temperature throughout the water column, and dissolved oxygen (Hanamoto 1987; Brill and Lutcavage 2001; Lee et al. 2005; Bigelow and Maunder 2007; Hyder et al. 2007). Others looked solely at catch rates and the different ways to assess the status of fish stocks. Bigelow and Maunder (2007) asked whether habitat or depth influence catch rates of pelagic species and found that analyses based solely on depth-specific catch rates can lead to a misinterpretation of abundance trends, despite the use of sophisticated statistical techniques. Hyder et al. (2007) used catch rates and their relation to variations in the oceanic conditions of the north Pacific basin, such as
sea-surface temperature, dissolved oxygen and surface currents, to infer migration and abundance of bigeye tuna. They found significant seasonal north-south catch rate migrations in which the maximum relative abundance migrated from the subtropical waters in September, to tropical waters in March when subtropical waters are coldest. The broad annual migrations were strongly influenced by the preferred near-surface temperature range. There were temporal patterns on different scales including inter-annual patterns, patterns associated with El Niño – Southern Oscillation (ENSO) and meso-scale patterns.

Recently, tagging data has proven to be a useful tool for learning more about the habitat utilization patterns of individual bigeye tuna. Tagging data has been used to confirm that bigeye tuna are associated with floating objects, such as offshore fishing aggregating devices (FAD) and that some individuals will associate with a specific FAD for over 30 days (Musyl et al. 2003). Also, while associated with a FAD, they do not exhibit their characteristic 'W-shape' dive pattern, which is used to describe a fish's movement up and down the water column throughout the day. Seamounts also play an important role in bigeye tuna migration and even though the exact mechanisms of that interaction are not fully understood, scientists have made progress recently towards better understanding some of the patterns. Bigeye do not associate with seamounts for extended periods of time, though adults associate with seamounts for longer periods than juveniles (Adam et al. 2003). Adam et al. estimated adult bigeye tuna residence time of 25 ±12 days at Cross Seamount. Aside from bigeye being attracted to any prey species that associate with seamounts, it is also thought that bigeye use seamounts as a type of
orientation point to help navigate their way through their larger migration pattern (Holland et al. 1999).

2.2 Fishing Technology

The efficiency of longline gear has also been investigated. Sharma and Leung (1999) analyzed the technical efficiency of longliners in Hawaii. They found that the vessels that are targeting swordfish, and those varying target by season, set or trip, tend to be less efficient that those vessels targeting tuna in all trips. They also examined fishing efficiency as it relates to other factors, such as the efficiency of vessels run by owners as compared to those run by hired captains. They also looked at experience of fishermen, fisher’s education level and a vessel’s size and age. They found owner-operated vessels to be more efficient than those operated by hired captains. The experience of fishers has a strong positive influence on technical efficiency. Sharma and Leung found a positive influence in vessel size and a fisher’s education level, but that influence was not significant. They also found that a vessel’s age had a negative influence on vessel efficiency.

Vessel size has also been a factor in fishers’ success. A survey conducted by O’Malley and Pooley (2001) provided baseline economic information associated with operating pelagic longline vessels in Hawaii in 2000. They classified the vessels in the Hawaii longline fleet by medium and large swordfish vessels and small (< 17.1 m), medium (17.1 to 22.5 m) and large tuna vessels (> 22.5 m). O’Malley and Pooley described many of the costs associated with longline fishing, such as the value of vessel,
including major additions to prepare the vessel to longline, minor engine repair, sales costs, and variable costs including fuel, oil, ice, bait and labor costs.

O’Malley and Pooley (2001) described physical characteristics of the fleet, fishing characteristics, such as number of trips per year, and how fishers have responded to some fishery management measures. The study found that of the vessels targeting tuna, the small vessels were the most profitable. These vessels had high gross revenues but lower fixed and variable costs, while large tuna vessels had higher gross revenue, they accrued higher costs, specifically variable costs. Large swordfish vessels were more profitable than smaller swordfish vessels, due to the higher gross revenues. It is worth noting that since 1994, the majority of active longline vessels in Hawaii have been medium sized.

2.3 Applications of GIS to Fisheries Research

The advent and development of computer technology and modeling software in recent decades has enabled researchers to quantitatively explore past and future patterns of different fisheries in specified ecosystems. However, historical fisheries data do not provide spatial information on landings and their trends suitable to support either a broad, global analysis or fine-scale spatial ecosystem modeling (Watson et al. 2004). If any worthwhile spatial analysis is to be done of the global fisheries, it is crucial that the catch data be reliable. Watson et al. (2004) and other researchers demonstrate both the difficulties in quantifying and displaying fisheries catch data and the potential benefit obtained from fine-scale, ecosystem modeling that examines the future impacts of management decisions on marine resources.
Watson et al. (2004) demonstrate the past constraints on fisheries analysis caused by inconsistent landings data and designed a program to overcome this and other issues. The authors collated international, regional and national data sets from many sources to map landings from 1950 to the present. A significant effort was dedicated to the issues of quality control. Queries based on year, country fishing and species fished are allowed from the resulting spatial dataset. Quantitative analyses have demonstrated that an increase in fishing effort is associated with large-scale reduction in biomass, reduced landings, and a reduction in size of fish landed. Their study was an example of a useful application being developed within a GIS that allows fisheries managers and fisheries policy makers to monitor the state of the fisheries around the world.

GIS has been demonstrated to be an effective tool for analyzing fishery patterns in the world’s oceans. Lee et al. (2005) analyzed the spatial and temporal distribution patterns of bigeye tuna in the Indian Ocean using the catch data of the Taiwanese longline fishery. They found that in the Indian Ocean, bigeye tuna were mainly distributed in tropical waters between 10° N and 15° S, although some scattered instances of high catches appeared outside this range. They also found that the distributional patterns shown by the CPUE and mass indices of bigeye tuna in the Indian Ocean were similar to those in the Pacific Ocean (Lee et al. 2005).

One very useful tool recently developed is Fishery Analyst. This is a customized graphical user interface, developed for ArcGIS by Francesca Riolo (2006) that allows the user to visualize and quantify spatial and temporal patterns in a fishery. It was initially developed to aid in the display and dissemination of fisheries information in American Samoa and has now been expanded to include Hawaii catch data. Fishery Analyst allows
for the visual comparison of maps of the same area on different dates and also allows for quantitative comparisons based on multiple parameters, such as catch, hook density, effort or CPUE.

The Department of Marine and Wildlife Resources (DMWR) in American Samoa has used Fishery Analyst to perform analyses based on hook density, catch density and CPUE using map outputs that display annual, monthly or quarterly figures for the areas including and surrounding American Samoa’s EEZ. Longline fishing was introduced to American Samoa in 1997 and since then has become the dominant fishing method.

Fishery Analyst also includes a feature that displays a series of maps as an animation to allow for comparisons through time. It is currently being used by the National Marine Fisheries Service (NMFS) to provide maps of large-scale fishery patterns to fishery policy makers.

Riolo first used the Wilcoxon signed-ranks test to test for a difference between the medians of two related samples and the Mann-Whitney U-test to look for a difference between the medians of two independent samples. She then found that the correlation of CPUE in the same area for sequential years is very low. This was due in part to the increase in total fished area through the years as the American Samoa fishery began to spread geographically and because of the generally random nature of fishing success.

Yu et al. (2009) sought to simulate Hawaii’s longline vessel activity by designing a prototype agent-based fishery management model to better predict how the fishery would respond to changes in regulatory policies. They broke the Pacific into five regions and showed how much fishing effort and catch fell into each region. The model successfully reproduced the spatial-temporal distribution patterns of fishing efforts by
simulating the behaviors of individual fishers (Yu et al. 2009). They tested the accuracy of the prototype by evaluating three alternative fishery regulatory policies: 1) no regulation; 2) annual cap of 17 turtle interactions; and 3) close the north central Pacific year round. They found that the model was able to capture the different behaviors of Hawaii’s longline fishers and to predict the responses of the fishery to changes in management regimes. For instance, a closure of the north-central region due to turtle interaction would lead fishers to relocate to other areas. Also, the turtle cap placed for each year has led fishers to concentrate their effort to the first two quarters of the year, as much as 70% (Yu et al. 2009).

While much is yet to be learned about bigeye tuna and the tuna fishery, the information acquired and shared by researchers provides a solid foundation upon which to build. Whether these fish are analyzed for the important biological role they play as apex predators of their pelagic ecosystem or simply for the economic role they play as a highly-valued ocean resource, researchers have accumulated a breadth of knowledge that has helped the public and fisheries managers better understand these fascinating creatures and there is still yet much to be learned.

2.4 Research Questions

My contribution to fisheries research will be to answer the following question: How have the levels of bigeye catch, CPUE and value by the Hawaii longline fishery changed annually, and what are their distributions, as they relate to distance from
Hawaii? To address this, I will develop maps that show:

- the annual geographic distributions of bigeye catch and CPUE from 1994 – 2008, and

Examining these maps will shed light on the large-scale patterns that have developed in Hawaii’s commercial longline bigeye tuna fishery and the possible impacts that changes, such as a rising cost of fuel, a drop in bigeye tuna prices or the establishment of more Marine Protected Areas (MPA) may have on the fishery.
CHAPTER 3. DATA & METHODS

3.1 Data

Described below are the datasets that were integrated for this study and the processing that was performed to display them. The longline logbook data was used to plot bigeye catch and CPUE, while plotting bigeye value was possible after a data integration process. The federal logbook system, implemented in 1990, is used to monitor the Hawaii-based commercial longline fishery. Logbooks are collected by the Fisheries Monitoring Branch (FMB) at the NOAA's Pacific Island Fisheries Science Center (PIFSC). The FMB collects, compiles, cross-checks and maintains the logbook data. An example of a logbook page is shown in Figure 3.1. The logbook data contain such fields as the set date, haul date, trip number, and the time and location for the beginning and end of the set and haul. It is the ‘Begin set’ points that are generally accepted by fishery scientists as the specific location of fishing effort. Logbooks also record the length of the mainline, whether the hooks were ‘Deep-set’ or ‘Shallow-set’ and the number of bigeye tuna kept and released, along with many other fields that are not relevant to this study. The shallow-sets were not included in this study, since they did not target bigeye.

The information collected in the logbooks pertaining to the number of hooks set allows for the calculation of the CPUE, which is the number of fish kept per thousand hooks set. This measure adjusts for variation in the length of the mainline and number of hooks set. CPUE is one of several factors considered in stock assessments, as it serves as one index of fish abundance.

The United Fishing Agency (UFA) collects information pertaining to each fish’s economic value and this is compiled by DAR. In 2002, DAR and PIFSC began a
cooperative effort to monitor market data electronically and the Marine Dealer Reporting System (MDRS) was implemented. Recently, PIFSC has integrated the longline logbook data with data collected by the UFA and the MDRS. The integrated data provide an historical record of the price per pound and the economic value of tuna caught and sold since 2000. This data integration makes it possible to associate the values of the fish caught with the trip in which they were caught. While it is not possible to associate a particular fish’s value with its corresponding set, it is possible to associate a fish’s value with its corresponding trip.

Access was granted to the longline logbook and UFA data under a confidentiality agreement with PIFSC. These data sets are both proprietary business and sensitive fishing trade information, which cannot be displayed publicly or shared in raw form. The standard for publicly displaying fishing activity data accepted by international fishery management organizations as non-confidential is to use 5° by 5° Lat/Long grid cells and to display data only for cells and time periods for which a minimum of three vessels were in operation. For instance, if in a given time frame, only two vessels fished in a particular cell, the data for that cell is considered confidential and cannot be displayed publicly. While the actual value for a given parameter of a confidential cell cannot be displayed, it is permitted to specify that a particular cell contains confidential data by labeling it as such.

The area for this study is limited to the portion of the central Pacific Ocean that has been fished by the Hawaii-based commercial longline fleet (50° N to 5° S and 125° to 180° W). A GIS was the primary tool used to display the data in order to examine the large-scale spatial-temporal patterns of the fishery. Other summary statistics presented
will be produced using the statistical software package StatView (SAS Institute Inc., San Francisco, CA, USA).

3.2 Data Processing and Methods

A 5° by 5° Lat/Long grid was created using ArcGIS software (Environmental Systems Research Institute, Redlands, CA, USA) and covers a total area of 36,156,080 km². Each of the 132 individual grid cells was given a unique identifier (Figure 3.2). A set of five concentric rings was created within the entire grid extending outward from Oahu, which was at the center of Ring 1 (Figure 3.3). The cell containing Oahu was assigned to Ring 1 because so much of its area is designated as part of the Main Hawaiian Islands Longline Fishing Prohibited Area that it is not worth keeping it as its own ring. The levels in catch, CPUE and value from the cells in each ring will be compared to establish whether there were differences as distance from Hawaii increased.

The purpose of the ring structure is to be able to conduct general comparisons of the distances traveled by fishers from Hawaii and how successful they were at those distances. However, there are factors involving the structure of the rings that require adjustments. First, each ring is comprised of more cells as they move outward from Hawaii, which means the area covered by a ring closer to Hawaii is less than a ring further away (Table 3.1). Second, the area of a cell is smaller the further north of the equator it is. Lastly, there are portions of cells in different rings that are off-limits to longline fishing because of either the presence of an MPA or because it consists of a portion of the EEZ of the Republic of Kiribati. Therefore, each ring was adjusted for the
actual area within it that is open to fishing, and each variable will be normalized by area, thus allowing for better comparisons between rings.

After the grid was created, the ‘Begin set’ points from the annual logbook data sets were plotted. The ‘Begin set’ points were joined to the grid cells, then summarized so that each cell would display a summary of the ‘Begin set’ points that occurred within each cell. The resulting output is a 5° by 5° Lat/Long grid for which each cell contains a summary of the selected field from the logbook data. Cells containing confidential data were labeled ‘Confidential’. With this data set, the sum or arithmetic mean of any field from the logbook data for each individual cell, such as the number of bigeye caught, the number of sets, number of hooks, mean CPUE, etc., can be displayed for the deep-set commercial longline fishery, and because the outputs exclude confidential data, they can be displayed to the public. The annual plots can be used to compare the long-term trends in the levels of catch, effort, CPUE and value in the fishery and how they relate to distance from Hawaii.

To display the geographic pattern of the economic value of the fishery, the mean center for the 'Begin set' points of each longline trip from 2000 – 2008 was calculated. Those points were joined with the integrated dealer data. If a vessel deployed seven sets during a trip, the location of the mean center of those 'Begin set' points is designated as the location of fishing for that trip. Vessels, generally, do not transit very much between sets and, considering the large size of the grid cells, most of a vessel’s sets usually end up in one to three adjacent grid cells. This makes it acceptable to associate the fish caught during a vessel’s trip to the particular grid cell in which most of its fishing effort took place. The output grids from those data display a near-estimate of how much money
fishers earned in each grid cell, before operating costs, based on the average price per pound of bigeye tuna for the day they were sold. Using this data, it will be possible to establish whether differences exist in the levels of catch, CPUE and value as distance from Hawaii increases, as seen between the different rings, and whether or not there were differences between different years within the same ring.
CHAPTER 4. RESULTS

4.1 General Results

The following results are for the deep-set commercial longline fishery in Hawaii for bigeye catch and CPUE for 1994 – 2008 and for bigeye value for 2000 – 2008. There were a total of 1,489,216 bigeye tuna caught by 166,538 sets deployed and the fishery had a total CPUE of 4.59. From 2000 – 2008, the fishery earned nearly $281 million. For all the years of the study combined, the cell with the highest number of bigeye tuna caught, 220,028, was in Cell 77, which is located just southwest of Kauai and is located in Ring 1 of the research area. This cell also had the highest value from 2000 – 2008 at $35.2 million. Interestingly, however, the cell with the highest CPUE was found far to the northwest of Kauai in Ring 3, Cell 51, and had a CPUE of 6.78 for the entire period.

As the fishery has grown through the years, there has been an increase in fishing effort, and thus catch and value, in cells farther away from Hawaii, as fishers have grown more willing to transit farther and farther to fish. There is a reduction in the levels of catch and value as distance from Hawaii increases, however, there is not necessarily the same decline in CPUE. Scatter plots of catch (Figure 4.1a), CPUE (Figure 4.1b) and value (Figure 4.1c) for all years combined demonstrate that for the period of this study the higher levels of catch and value occurred closer to Hawaii. The levels of catch and value drop by about 76% on average after 1,000 km; then, past 1,700 km, drop by another 76% on average. For CPUE, that drop-off is much less drastic. The drop in CPUE after 1,000 km is only about 7% on average, followed by 8% after 1,700 km. The highest CPUE occurred in a cell that has its center at a distance at just over 1,600 km from Oahu.
Also, the minimum and maximum CPUE were at distances from Honolulu that differed by less than 80 km.

Figure 4.2 shows the spatial distribution of the total number of bigeye tuna caught in each grid cell. It is quite apparent that the highest levels of catch were concentrated around the main Hawaiian Islands. Also, fishers appear to travel farther to the south of Oahu to fish than they do to the north. Longline fishers are generally known to travel north to fish for swordfish. They did not travel further north than 40° N, and were not very successful north of 35° N. They also did not fish south of the equator, but were quite successful in one cell near the equator, especially west of 160° W. No fishing that was considered confidential occurred west of 175° W or east of 135° W. There was confidential fishing that occurred just west of the dateline and as far east as 125° W.

Figure 4.3 maps the spatial distribution of the CPUE for the period of the study. The distribution of bigeye CPUE is not as simple to discern as bigeye catch. There are high levels of CPUE scattered throughout the research area, with the highest CPUE, 6.78, occurring in a cell far away from Hawaii, in Ring 3. Even the 2nd highest CPUE was found far south of Hawaii, in Ring 3. However, the lowest levels of CPUE were also found on the perimeter of the fished area, particularly the south-eastern portion of the research area. Also, all of the cells in Ring 1 experienced relatively high levels of CPUE. This map demonstrates that fishers experienced relatively high catch rates for the period of the study in waters directly surrounding Hawaii, but also that several cells much farther away from Hawaii experienced even higher catch rates.

Figure 4.4 from the integrated data shows the geographic distribution of the sum of the economic yield from bigeye tuna sold in each grid cell from 2000 to 2008. Fishers
grossed more than $280.9 million in those nine years, with the highest value being reached in Cell 77, in Ring 1, with a value of more than $35.2 million. The pattern for value looks very similar to that of catch, but the cells with higher value are more concentrated around the main Hawaiian Islands. There were a couple of cells to the southwest of Oahu that reached relatively high values.

4.2 Temporal Variations – Annual and Quarterly Trends in the Fishery

There are notable differences between the years in the levels of catch, CPUE and value of the fishery. The robust coefficient of variation (RCV) ([interquartile range * 0.7413 / median] x 100) for the annual catch and CPUE from 1994 to 2008 are 61.7% and 23.4%, respectively, and is 21.9% for the annual value of the fishery from 2000 to 2008. This measure of dispersion indicates that there has been less variation throughout the years in value as compared to levels of catch and CPUE. The quarterly variations in the levels of catch and value of the fishery indicate that there is less variation for the 1st and 4th quarters as compared with the 2nd and 3rd quarters (Table 4.1). The 1st and 4th quarters of catch and value have a RCV that is lower than the 2nd and 3rd quarters, but that is not the case for CPUE. Also, for CPUE, the differences in the RCV between the 1st and 4th quarters versus the 2nd and 3rd is much less than it is for catch and value. This indicates that there was less variation between quarters for CPUE than for catch and value, that the 3rd quarter experienced the most variation of catch and value through the years, and that the 1st quarter had the least variation of catch, CPUE and value.
4.2.1 Annual and Quarterly Catch

Annual bigeye tuna catch has generally shown an increase through the years of the study (Figure 4.5). In 2008, there were 150,834 bigeye caught, a 5% reduction from 2007, which saw the highest annual level with 158,086 bigeye caught. This was more than a 4-fold increase from 1994. A quarterly breakdown gives some insight into the seasonal trends of the fishery by showing that the highest percentage of bigeye catch occurs in the 4th quarter. The bigeye catch for the 4th quarters during the period of 1994 – 2008 accounted for 37.4% of the total catch, followed by the 1st quarter’s 27.3%. The 2nd and 3rd quarters were very similar, accounting for 17.7% and 17.6%, respectively. An annual graph of the catch by quarter shows that the 1st quarters experienced the highest catch for 12 of the 15 years (Figure 4.6). The 3rd quarters experienced the lowest catch from 1994 – 1998, but since then has alternated with the 2nd quarters for the lowest catch levels.

4.2.2 Annual and Quarterly Effort

One measure of fishing effort is the number of sets that fishers deploy. Longline sets deployed by the Hawaii longline fishery have increased every year since 1994 except during 2006 (Figure 4.7). Increases of sets of at least 1,900, occurred in 2001 and 2002. Another record in the number of sets was reached in 2008 when 16,600 sets were deployed, more than a 3-fold increase from 1994. Sets deployed during the 4th quarters of the study accounted for 31.7% of the total sets, followed by the 1st quarter’s 25.4%. The 2nd and 3rd quarters accounted for 22.0% and 20.9%, respectively. The most sets were
deployed in the 4th quarter of every year since 1994 and the 1st quarter had more sets deployed than the 2nd and 3rd quarters for all but three years (Figure 4.8).

Another measure of fishing effort is the number of hooks that fishers set. The number of hooks set increased every year from 1994 – 2008. In 2008, more than 37.4 million hooks were set (Figure 4.9). This is a 6-fold increase from the number of hooks set in 1994. The breakdown for the percentage of the total number of hooks set for each quarter is almost identical to that of the percentage of sets by quarter. Every year, more hooks were set in the 4th quarter and, as with the number of sets, the 1st quarter had more hooks set than the 2nd and 3rd quarters for all but three years (Figure 4.10).

4.2.3 Annual and Quarterly CPUE

As a reminder, the CPUE is measured as the number of fish kept per every thousand hooks set. The CPUE for all years combined is 4.59 ± 1.35 (standard deviation). As Figure 4.11 shows, bigeye tuna CPUE in Hawaii has fluctuated since 1994 and peaked in 1998 when it reached 6.73. In 2008, the CPUE was 4.03, which is a decrease of 0.32, or 7%, from 2007. The lowest occurred in 2006, with a CPUE of 3.67. This makes a range in CPUE for the whole time period of 3.06. After 1998, however, bigeye CPUE has remained rather steady, falling within a range of 1.93. It is not very encouraging, however, that 2008 had the 4th lowest CPUE since 1994, and that since 1999 there have been twice as many decreases than increases from one year to the next. The quarterly breakdown of CPUE shows the 1st and 4th quarters have alternated in having the highest CPUE and have remained relatively close since 1999 (Figure 4.12). Both the 1st and 4th quarters had a higher CPUE than the 2nd and 3rd quarters for ten of the fifteen years.
4.2.4 Annual and Quarterly Value

A new record was set in 2008 when the fishery reached an economic value of just over $48.1 million (Figure 4.13). This is more than an 18% increase from the previous record set in 2007 when the fishery yielded more than $40.7 million. There was, by 2008, more than a 2.5-fold increase in gross value from 2001, the lowest for the study. As with the quarterly breakdowns of bigeye effort and catch, the highest percentage of total bigeye value belongs to the 4th quarter. Bigeye value for the 4th quarters during the period of 2000 – 2008 accounted for 31.8% of the total, followed by the 1st quarter with 24.6%. The 3rd and 2nd quarters accounted for 22.8% and 20.8%, respectively. A quarterly breakdown of the data shows that the 4th quarter had the highest value every year except for 2000, when the 1st quarter had the highest value (Figure 4.14). The 1st quarter had a higher value than the 2nd and 3rd quarters for five of the last nine years. Otherwise, the 2nd and 3rd quarters have fluctuated quite a bit through the years.

4.3 Geographic Distribution of Effort, Catch and Value

The number of cells in the research area that experienced fishing has increased through the years, indicating that fishing effort has become more dispersed geographically (Figure 4.15). The number of cells that experienced fishing has nearly doubled since 1994. The highest number of cells fished, including confidential cells, was reached in 2002, when 47 cells experienced fishing. There has been some fluctuation since then, but there was still wide distribution in 2008 when 44 cells were fished, and since 2000, there has not been fewer than 32 cells that experienced fishing each year. This demonstrates that, through the years, fishers have been willing to travel farther away
from Hawaii to fish, despite the rising cost of fuel. While the levels of effort, catch and value are not nearly as high or as consistent as they are directly surrounding the main Hawaiian Islands, more and more peripheral cells have experienced fishing through the years and a few of those areas have intermittently had relatively high levels of catch, CPUE and value.

There is, however, a limit as to how far fishers have been willing to travel. Of the 132 cells that make up the research area, 65 of them did not experience any fishing. The vast majority of ‘Confidential’ cells were on the periphery of the research area. This was expected because the distance to these cells is so great that fishers are unlikely to transit to them to fish. This is at least partly because fishers are aware that bigeye tuna are only found so far north or south of Hawaii, but mainly because it takes a lot of time and fuel to transit to areas in the periphery and because a fresh fish will be worth more than an older fish. This pattern of the 'Confidential' cells being located on the periphery is demonstrated in the annual maps for most years of the study.

Regarding the distribution of fishing effort, as it relates to distance, for all the years of the study combined, the majority of the sets deployed were found in the ring containing Oahu, Ring 1 (Table 4.2). As a reminder, each ring was normalized by its fishable area. Ring 1 accounted for a vast majority of total sets, followed by Ring 2. Ring 1 had five times as many sets as Ring 2, and 17 times as many as Ring 3. Similarly, the vast majority of fish were caught in Ring 1, with just over five times as many fish caught in Ring 1 than in Ring 2, and almost 14 times as many as Ring 3. For the years 2000 – 2008 combined, the majority of the value was also found in Ring 1, with over four times as much value than in Ring 2, and almost 14 times as much as Ring 3. Though the fishery
spread out geographically during the period of the study, the vast majority of the total
effort, catch and value were found near the main Hawaiian Islands, and that the levels of
each decrease steadily as one moves further from Hawaii. The steepest decline occurred
from Ring 1 to Ring 2.

4.4 Annual Geographic Distribution of Bigeye Catch, CPUE and Value

The annual maps of bigeye catch demonstrate the growth of the fishery through
the years, in regards of the levels of bigeye catch and in fishers’ growing willingness to
travel farther from Hawaii (Figure A-1 to A-15). The fishery has spread out
geographically through the years, but it does appear to have reached a limit, such that
Rings 4 and 5 have not experienced notable increases in the last several years. They have
experienced very little to no fishing effort or catch for most years of the study. In fact,
Ring 5 only experienced fishing in five years of the study (1998, 2000 – 2002 and 2007),
but Ring 4 has experienced fishing every year since 1998.

An annual breakdown of actual bigeye catch by ring shows that Ring 1 has had
the highest levels of bigeye catch every year of the study, when normalized by area
(Figure 4.16). Ring 2 has had the 2nd highest levels of catch for all 15 years of the study,
while Ring 5 has had the lowest levels of catch for all of the five years that it experienced
fishing. The annual variations, as RCV, for Rings 3, 4 and 5 were much higher than for
the first two rings, indicating that fishers experienced much less variation, in terms of
their catch, closer to Hawaii (Table 4.3).

While there have been higher levels of catch, mainly as a result of the higher
levels of effort, we have also seen that this increase in effort has not necessarily resulted
in the same increase in CPUE through the years. A look at the annual maps of CPUE shows a less coherent pattern through the years (Figure B-1 to B-15). For some years, the highest CPUE occurred far away from Hawaii. The annual breakdown of each ring’s mean CPUE is different than that of bigeye catch (Figure 4.17). There is alternation between which ring had the 2\textsuperscript{nd} highest mean CPUE each year, but Ring 1 had the highest mean CPUE for every year of the study except 2007, when it was exceeded by Ring 3. Regarding the annual mean CPUE fluctuations among rings, the RCV of Ring 2 is half that of Ring 1, then each ring increases as you go out from Ring 2 (Table 4.3). Ring 5 has the highest RCV. This measure of dispersion of mean CPUE among rings supports that fishers experienced less fluctuation in CPUE within a certain distance from Hawaii, then increased the farther they fished.

The next set of maps shows the annual geographic distribution of the value from bigeye tuna sold (Figure C-1 to C-9). These maps are similar to those showing the annual geographic distribution of bigeye catch, in that, the levels of bigeye value increase and become more widely distributed over time, and that the majority of the value of bigeye caught is concentrated around the main Hawaiian Islands. An annual breakdown of bigeye value by ring shows that Ring 1 has had the highest levels of bigeye value every year since 2000 (Figure 4.18). Ring 2 has had the 2\textsuperscript{nd} highest levels of value every year, and appears to have increased its difference from the other rings each year since 2004. Since 2000, Ring 5 has had very low levels of bigeye value. The RCV of each ring increases as you go out from Ring 1 until you reach Ring 4 (Table 4.3). Ring 3 has the highest variation.
4.5 Effect of Management Decisions and Marine Protected Areas on the Fishery

There were few management decisions that appear to have had an impact on the spatial distribution of the deep-set longline fishery. The vast majority of management measures enacted during the period studied were aimed at reducing the interactions of protected species with shallow-set longline gear, and mostly involved gear restrictions and temporary area closures. One of the management measures that clearly affected the behavior of the deep-set fishery was the emergency rule enacted in December 1999, and subsequently extended through December 23, 2000, that prohibited any longline fishing by Hawaii-based vessels north of the Hawaiian Islands (65 FR 37917). The map for the year 2000 shows the absence of any fishing in those cells (Figure A-7). Every subsequent year experienced fishing in cells north of the Hawaiian Islands. Other than that management measure, there were not any apparent patterns in the distribution of the fishery that could be attributed to any management measures that were enacted during the period of the study.

Regarding other area closures, the Main Hawaiian Islands Longline Fishing Prohibited Area takes up a large portion of Cell 66, containing Oahu, and a small area in neighboring cells (Figure 4.19). Even though this fishing prohibited area has been in place since before the period of the study, the remaining part of Cell 66 has had high annual levels of effort and catch. However, it has never had the highest level of catch in Ring 1. This means that fishers exert heavy pressure on the portion of that cell that is not closed to longlining and they also take advantage of the time of year, from Oct. 1 to Jan. 31, when the closure extension area is not in place. That extended closure area is covered with ‘Begin set’ points during that time of year when it is not in place. This requires less
transit by fishers during those winter months when effort, and subsequently catch, are highest and they also do not want to transit as far because of the risk of the fishery reaching the yearly quota and being shut down until the following calendar year. If they get the notice that the fishery is going to be shut down for the remainder of the year, they want to be as close to port as possible.

Regarding the four other MPAs that fall inside of the research area, Johnston Atoll, Howland and Baker Islands, Jarvis Island, Kingman Reef and Palmyra Atoll, the Hawaii longline fishery will likely not be greatly affected by their establishment (Figure 4.20). For instance, the Howland and Baker Islands MPA is about 3,200 km southwest of Hawaii and did not experience any fishing effort during the years of the study. Two of the four cells containing the Jarvis Island MPA did not experience any fishing effort. Regarding the two cells that experienced some fishing during the study, Cell 113 was fished for 11 years of the study and Cell 114 for three years (Table 4.4). They have their center at 2,276 km and 2,211 km away from Oahu, respectively. In Cell 113, 7,838 bigeye were caught by 725 sets, comprising 0.4% of the total sets and 0.5% of the total catch. In Cell 114, 711 bigeye were caught by 126 sets in Cell 114, making up 0.08% of the total sets and 0.05% of the total catch. The Jarvis Island MPA takes up less than 10% of each of these cells and its establishment will most likely not have any significant impact on fisher behavior.

One MPA that will likely have an effect on fisher behavior is designated around Kingman Reef & Palmyra Atoll, in Cell 101. This cell's center is 1,743 km from Oahu and experienced fishing all 15 years of the study (Table 4.4). There were 61,038 bigeye tuna caught by 5,314 sets, which is 3.2% of the total sets and 4.1% of the total catch. The
area of this MPA takes up a large portion of this cell and will likely have an effect on fisher behavior. This is also the case for the Johnston Atoll MPA which is even closer to Hawaii, about 1,300 km, mostly in Cell 76. This cell experienced fishing all 15 years of the study and had 46,641 bigeye caught by 5,692, which comprised 3.4% of the total sets and 3.1% of the total catch. It will be interesting to see what effect, if any, these MPAs will have on fisher behavior in future years.
CHAPTER 5. DISCUSSION AND CONCLUSIONS

Bigeye tuna stocks in the Pacific Ocean have experienced increased pressure prior to 1994, and since then, fishing effort has continued to increase in every regard: the number of trips taken, and the number of sets and hooks deployed. Seasonally, all measures of effort are greatest in the 4th quarter, followed by the 1st quarter. This distribution of effort throughout the year results in the higher levels of catch and value occurring in the 4th and 1st quarters. Hawaii-based fishers have become more willing to travel longer distances to fish for bigeye and some outer areas have frequently experienced rather high levels of catch, CPUE and value. However, no matter how far fishers have been willing to travel each year, the bulk of the effort, catch and value has been located near the main Hawaiian Islands.

While all levels of effort, catch and value have increased during the study period, levels of CPUE have not seen equivalent increases. CPUE peaked in 1998, then dropped, and has stayed within the relatively small range of 1.9 since 1999, versus 3.1 for the entire period of the study. This may not automatically be a cause for great concern, but, with all levels of effort having increased, it does make one wonder whether the days of very high CPUE are behind us and about the overall sustainability of the fishery. Even though fishers have not experienced higher levels of CPUE during the last several years, they have certainly experienced higher levels of bigeye value since 2000. However, the ultimate goal is to maintain a sustainable fishery, and a continued reduction in CPUE would, at a certain point, make fishers wonder if the levels of catch were even worth their effort.
The high levels of value not only have to do with high levels of catch, but also with the increasing average price of bigeye tuna since 2002. While there have not been any increases in the average price of bigeye per pound from one year to the next of over fifty cents per year, the year 2008 saw the 2nd greatest increase and set the highest average price per pound during the period of the study. This increase in the average price of bigeye may have several explanations, but it corresponds with the increase in the economic yield of the fishery for that year. This was also the case in 2007 when catch levels increased from the prior year and the average price of bigeye dropped only slightly, but stayed relatively high.

It appears that even while the supply of bigeye tuna has remained consistent, and even increased during several years of the study, the demand for bigeye has increased in the last several years, especially as Hawaii’s population has increased. If Hawaii’s longline fishers were to experience any drastic declines in bigeye catch, the price of bigeye may increase even more, which may be of some concern to consumers who enjoy bigeye tuna at a relatively reasonable price.

5.1 Research Limitations and Confidentiality Issues

The required use of large grid cells prevented a more detailed look at the spatial distribution of the fishery. Also, no vessel names are used in this study and that prevents the public and, more importantly, other fishers from knowing which vessels fished in a given area. However, if a fisher is able to see that fishers have had great success in a given area, it does not matter who those fishers are, one may be motivated to fish that area as well, creating more competition for the bigeye tuna in that area. In any case, the
fact is that bigeye tuna are highly migratory and occur in whatever areas meet their preferred habitat specifications and those areas change through the year and throughout the years. Perhaps a compromise can be made between the fishers, fishery managers and organizations that wish to perform a similar study in the future to be able to present more detailed spatial information without compromising fishers’ trade secrets. Cells that were 2.5° or 1.5° would, in my opinion, still meet that goal.

5.2 Management Issues Moving Forward

One factor that will now come into play at the end of each year is the 3,763 mt quota set by the WCPFC for bigeye from 2009 through 2011. It is unclear what the quota will be for the following years, assuming the WCPFC sets a quota. The implication of having this quota in place is that if longline fishers reach it before the end of the year, they can no longer sell bigeye tuna that were caught west of 150° W. As it relates to distance from Hawaii, this means they cannot fish inside of Ring 1, thereby likely increasing levels of effort in the outer rings, at least in the cells to the east of 150° W. It is unclear what effect these quotas, and the threat of reaching them, will have in the long run on fishers’ willingness to travel farther to fish for bigeye, but it will certainly be interesting to watch it unfold.

It has been demonstrated that while there has been some incentive to travel farther from Hawaii to fish for bigeye tuna, higher levels of catch, CPUE and value have been reached closer to the main Hawaiian Islands and those higher levels are less variable. Fishers take less risk and spend less in operational costs by staying closer to Hawaii. The question that arises is: how is the fishery best managed knowing that the concentration of
fishing effort takes place around the main Hawaiian Islands? Perhaps fisheries managers could create some incentive for fishers not to fish those areas so heavily throughout the entire year in order to avoid excessive pressure on fish stocks. It is worth noting that one of the main reasons the Council had for establishing the Main Hawaiian Islands Longline Fishing Prohibited Area was to help prevent local overfishing.

One measure, which has been proposed to the Council, could be to shift the year of the fishery away from the calendar year. This could reduce the likelihood of the fishery having to be shut down in December when fishers generally have more success and get better prices for their catch. This would also reduce pressure on fish stocks because fishers would not make that rush at the end of each year to catch as many fish as possible. Instead, if the fishing year ended in September, fishers would already know going into the summer, when they are least active, how close they are to reaching the quota.

Another possibility could be to implement a quarterly quota. If a quarter’s quota is met, no more fishing would be allowed until the next quarter. If it is not met, however much of the quota was not reached, could carry over to the next quarter, or as a conservation measure, could not carryover, thus reducing the annual pressure on tuna stocks over all. These are just a couple of ideas that could help take some pressure off of tuna stocks and still allow fishers to operate a profitable business.

5.3 Conclusion

Fishers have been more willing to travel farther from Hawaii to longline, even considering today's high fuel prices and the higher costs of most expenses on longer trips. Certainly, refrigerated hulls and advanced navigation tools have made traveling farther to
fish easier. Perhaps fishers are beginning to feel the high levels of competition near the main Hawaiian Islands and decided to venture out, then the varying degrees of success only encouraged them to risk traveling far for the chance of the big catch. As seen in the annual maps, not only have the levels of CPUE around the main Hawaiian Islands not been very high, as compared with some outer areas, but some areas outside of the main Hawaiian Islands have had relatively high levels of catch, CPUE and value, such as around Johnston Atoll and Palmyra Atoll. Since around 2000, these cells began to see more effort, catch, and ultimately, value. It will be interesting to see the geographic patterns of the fishery in the next several years, and whether or not fishers will find successful fishing areas away from Hawaii.

Fisheries managers have acknowledged that bigeye tuna are currently being overfished, that bigeye mortality exceeds the stock's ability to sustain the MSY. This has prompted at least one of the RFMOs in the Pacific Ocean to establish catch limits, which some say are still too high. It would likely be in the best interest of all parties involved if fisheries managers were to reduce these catch limits, at least temporarily, despite the push-back from fishers and consumers. It is easy to recognize that telling fishers to fish less has implications on their livelihoods, but a long-term, sustainable fishery is very much in line with their goal of making a living. If the longline tuna fishery were to collapse, all of the effort put into managing it would have been for naught, and fishers would still be out of a livelihood.

The economic value of our ocean resources is enormous, but the health of the ocean and its ability to provide us with those resources is not something that can be taken for granted. A delicate balance needs to be found between people’s desire to eat fish, the
economic needs of the fishers who catch the fish, and the overall health of the populations of the fish we catch. The research continues with many people wondering what the future holds for bigeye tuna, knowing the important role they play in regards to their environment and to the many people that rely on them for food and income.

It is my hope that this study sheds light on some of the spatial and temporal trends of Hawaii’s longline tuna fishery, and some of the issues it continues to face moving forward. What is clear is that there is not one simple solution to this issue, as there rarely is. The ocean’s natural resources are in high demand and there is no sign that there will be a reduction any time soon. To maintain a sustainable fishery there needs to be cooperation by all parties involved. This begins with the collection of useful data by fisheries scientists to help better understand what is occurring in our oceans and what fishers are actually doing, followed by the dissemination of this data to fisheries managers and the public. Through the application of useful science and the cooperation of all parties involved, the proper policies can be implemented that will help ensure that a sustainable longline fishery is able to operate in Hawaii for many years to come.


______. 2009. Resolution on a multi-annual program for the conservation of tuna in the eastern Pacific Ocean in 2009-2011. 80th Meeting. La Jolla, CA.


### Table 3.1. Fishable area in each ring of research grid.

<table>
<thead>
<tr>
<th>Ring</th>
<th># of cells</th>
<th>Area (km²)</th>
<th>Area of ring off-limits to fishing (km²)</th>
<th>Area of Kiribati EEZ in Ring (km²)</th>
<th>Remaining area open to fishing (km²)</th>
<th>Remaining % of Fishable Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>9</td>
<td>2,555,133</td>
<td>321,046</td>
<td>0</td>
<td>2,234,088</td>
<td>10.7%</td>
</tr>
<tr>
<td>Ring 2</td>
<td>12</td>
<td>3,385,231</td>
<td>135,133</td>
<td>0</td>
<td>3,250,099</td>
<td>15.5%</td>
</tr>
<tr>
<td>Ring 3</td>
<td>16</td>
<td>4,474,191</td>
<td>164,097</td>
<td>92,277</td>
<td>4,217,818</td>
<td>20.1%</td>
</tr>
<tr>
<td>Ring 4</td>
<td>20</td>
<td>5,529,101</td>
<td>90,141</td>
<td>382,966</td>
<td>5,055,994</td>
<td>24.1%</td>
</tr>
<tr>
<td>Ring 5</td>
<td>24</td>
<td>6,541,930</td>
<td>23,064</td>
<td>303,631</td>
<td>6,215,236</td>
<td>29.6%</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>22,485,586</td>
<td>733,481</td>
<td>778,874</td>
<td>20,973,235</td>
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</tr>
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</table>


<table>
<thead>
<tr>
<th>Qtr</th>
<th>Catch</th>
<th>CPUE</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qtr 1</td>
<td>30.8%</td>
<td>14.8%</td>
<td>13.5%</td>
</tr>
<tr>
<td>Qtr 2</td>
<td>65.1%</td>
<td>18.8%</td>
<td>38.2%</td>
</tr>
<tr>
<td>Qtr 3</td>
<td>145.8%</td>
<td>17.3%</td>
<td>53.0%</td>
</tr>
<tr>
<td>Qtr 4</td>
<td>43.3%</td>
<td>38.6%</td>
<td>26.4%</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Ring</th>
<th>Total Sets</th>
<th>% of Total Sets</th>
<th>Sets per km²</th>
<th>Total Catch</th>
<th>% of Total Catch</th>
<th>Catch per km²</th>
<th>Total Value</th>
<th>% of Total Value</th>
<th>Value per km²</th>
</tr>
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<tbody>
<tr>
<td>Ring 1</td>
<td>119,597</td>
<td>71.8%</td>
<td>0.05353</td>
<td>1,035,646</td>
<td>69.5%</td>
<td>0.4636</td>
<td>$190,171,563</td>
<td>67.7%</td>
<td>85.12</td>
</tr>
<tr>
<td>Ring 2</td>
<td>32,149</td>
<td>19.3%</td>
<td>0.00989</td>
<td>296,983</td>
<td>19.9%</td>
<td>0.0914</td>
<td>$62,610,027</td>
<td>22.3%</td>
<td>19.26</td>
</tr>
<tr>
<td>Ring 3</td>
<td>13,200</td>
<td>7.9%</td>
<td>0.00313</td>
<td>141,871</td>
<td>9.5%</td>
<td>0.0336</td>
<td>$26,097,572</td>
<td>9.3%</td>
<td>6.19</td>
</tr>
<tr>
<td>Ring 4</td>
<td>1,416</td>
<td>0.9%</td>
<td>0.00028</td>
<td>13,803</td>
<td>0.9%</td>
<td>0.0027</td>
<td>$2,011,611</td>
<td>0.7%</td>
<td>0.40</td>
</tr>
<tr>
<td>Ring 5</td>
<td>176</td>
<td>0.1%</td>
<td>0.00003</td>
<td>913</td>
<td>0.1%</td>
<td>0.0001</td>
<td>$107,471</td>
<td>0.04%</td>
<td>0.02</td>
</tr>
</tbody>
</table>

166,538 1,489,216 $280,998,244

<table>
<thead>
<tr>
<th>Ring</th>
<th>Catch</th>
<th>CPUE</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.2%</td>
<td>18.5%</td>
<td>26.7%</td>
</tr>
<tr>
<td>2</td>
<td>53.6%</td>
<td>9.3%</td>
<td>45.6%</td>
</tr>
<tr>
<td>3</td>
<td>145.7%</td>
<td>23.5%</td>
<td>96.3%</td>
</tr>
<tr>
<td>4</td>
<td>124.7%</td>
<td>38.0%</td>
<td>38.3%</td>
</tr>
<tr>
<td>5</td>
<td>120.9%</td>
<td>95.1%</td>
<td>55.4%</td>
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</table>


<table>
<thead>
<tr>
<th>Cell</th>
<th>Ring</th>
<th>Distance (km) to Center</th>
<th>Number of years fished</th>
<th>Total Sets</th>
<th>% of Total Sets</th>
<th>Total Catch</th>
<th>% of Total Catch</th>
<th>Mean CPUE</th>
<th>Total Value</th>
<th>% of Total Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>2</td>
<td>1,182</td>
<td>15</td>
<td>5,692</td>
<td>3.4%</td>
<td>46,641</td>
<td>3.1%</td>
<td>4.08</td>
<td>$8,071,975</td>
<td>2.9%</td>
</tr>
<tr>
<td>101</td>
<td>3</td>
<td>1,743</td>
<td>15</td>
<td>5,314</td>
<td>3.2%</td>
<td>61,038</td>
<td>4.1%</td>
<td>5.70</td>
<td>$11,490,602</td>
<td>4.1%</td>
</tr>
<tr>
<td>113</td>
<td>4</td>
<td>2,276</td>
<td>11</td>
<td>725</td>
<td>0.4%</td>
<td>7,838</td>
<td>0.5%</td>
<td>5.28</td>
<td>$1,044,705</td>
<td>0.4%</td>
</tr>
<tr>
<td>114</td>
<td>4</td>
<td>2,211</td>
<td>3</td>
<td>126</td>
<td>0.08%</td>
<td>711</td>
<td>0.05%</td>
<td>2.41</td>
<td>$91,582</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
FIGURES

Bigeye Tuna (Thunnus obesus)

Pectoral fin is yellow and long and extends past the first dorsal fin

Underside of the liver (internal) has striations

Second dorsal fin and anal fin are not elongate

Figure 1.1. Image with identifying features of bigeye tuna (Thunnus obesus). Source: Oregon Dept. of Fish and Wildlife <http://www.dfw.state.or.us/mrp/salmon/fishid/FishIDTunas.asp>.

Figure 1.2. Global distribution of bigeye tuna shown in red. Source: Food and Agriculture Organization, 2007 <http://www.ffa.int/mcs/node/324>.
Figure 1.3. Temporal variation in the number of active longline vessels based and landing in Hawaii, 1994-2008. Source: NMFS, 2009.

![Temporal Variation Diagram](Image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean</th>
<th>StDev</th>
<th>CV</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>116.9</td>
<td>10.6</td>
<td>112.6%</td>
<td>100</td>
<td>129</td>
</tr>
</tbody>
</table>

Figure 1.4. Swordfish set compared to Tuna set by longline fishers. Source: Hawaii Longline Association, 2005


![Swordfish vs Tuna Sets](Image)
Figure 1.5. Mean annual price per pound of bigeye tuna in Hawaii, 1994 – 2008. Source: NMFS, 2009.

Figure 1.6. Map of convention areas for Regional Fishery Management Organizations in the Pacific Ocean. Source: NOAA PIRO, 2007.
Figure 1.7. U.S. Exclusive Economic Zone – waters managed by the Western Pacific Regional Fishery Management Council (WPRFMC). Source: NOAA PIRO, 2007.

Figure 1.8. Percentage of bigeye caught from each management area in the Pacific by the Hawaii longline fleet, 1994 – 2008. Source: NMFS, 2009.

Figure 1.10. Longline fishing prohibited areas around the Main Hawaiian Islands. Source: NOAA PIRO, 2010.
Figure 3.1. Federal longline logbook used to collect data from Hawaii commercial longliners.
Figure 3.2. Grid of research area (50°N to 5°S and 175°E to 125°W).
Figure 3.3. Grid of research area and 5 rings around Oahu.
Figure 4.1. Scatter plots showing the levels of (a) catch and (b) CPUE for all cells fished versus distance from Honolulu for all years combined, 1994 – 2008 (n=48), and (c) value, 2000 – 2008 (n= 44).
Figure 4.2. Geographic distribution of the sum of bigeye tuna catch.
Figure 4.3. Geographic distribution of the arithmetic mean of bigeye tuna CPUE.
Figure 4.4. Geographic distribution of the value of bigeye tuna sold.
Figure 4.5. Annual bigeye tuna catch by Hawaii's deep-set longline fishery, 1994 – 2008.

Figure 4.6. Annual bigeye tuna catch by Hawaii's deep-set longline fishery by quarter, 1994 – 2008.
Figure 4.7. Annual number of sets deployed by Hawaii's deep-set longline fishery, 1994 – 2008.

Mean = 10,610.8  
StDev = 4,468.3  
CV = 42.1%  
Min = 4,359  
Max = 16,600

Figure 4.8. Annual number of sets deployed by Hawaii's deep-set longline fishery by quarter, 1994 – 2008.
Figure 4.9. Annual number of hooks set by Hawaii's deep-set longline fishery, 1994 – 2008.

Figure 4.10. Annual number of hooks set by Hawaii's deep-set longline fishery by quarter, 1994 – 2008.
Figure 4.11. Annual bigeye tuna catch per unit of effort (CPUE) by Hawaii's deep-set longline fishery, 1994 – 2008.

Figure 4.12. Annual bigeye tuna CPUE by deep Hawaii's deep-set longline fishery by quarter, 1994 – 2008.
Figure 4.13. Annual value of bigeye tuna sold by Hawaii's deep-set longline fishery, 2000 – 2008.

Figure 4.15. Annual number of 5°x5° Lat/Long cells in research area that experienced fishing. This includes cells that were considered confidential.

Figure 4.16. Annual number of bigeye caught in each ring normalized by fishable area, 1994 – 2008.
Figure 4.17. Annual mean CPUE by ring normalized by fishable area, 1994 – 2008.

Figure 4.18. Annual value of bigeye caught in each ring normalized by fishable area, 2000 – 2008.
Figure 4.19. Main Hawaiian Islands.
Figure 4.20. Areas off-limits to longline fishing.
APPENDIX A

A-1

Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1994

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1995

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1996

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1997

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1998

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 1999

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for a specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2000

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2001

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.

- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2002

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2003

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2004

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2005

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2006

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2007

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.

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<tr>
<th>Cells_Fished</th>
<th>Sets</th>
<th>SUB_CATCH</th>
<th>MEAN_CATCH</th>
<th>MIN_CATCH</th>
<th>MAX_CATCH</th>
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</thead>
<tbody>
<tr>
<td>32</td>
<td>86,952</td>
<td>157,664</td>
<td>4,936.36</td>
<td>71</td>
<td>27,125</td>
</tr>
</tbody>
</table>

Nautical Miles
Number of Bigeye Tuna Caught by Hawaii Deep-set Longline Fishery 2008

- The value for each cell is the sum of the number of bigeye tuna caught by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
APPENDIX B

Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 1994

Catch per unit of effort

- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.00
- 11.00 - 13.00
- > 13.00

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUB_CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
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<tbody>
<tr>
<td>4,921</td>
<td>28,676</td>
<td>6.36</td>
<td>1.52</td>
<td>1.03</td>
<td>5.37</td>
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</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 1995

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUM_CATCH</th>
<th>MEAN_CPOE</th>
<th>STD_CPOE</th>
<th>MIN_CPOE</th>
<th>MAX_CPOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.095</td>
<td>43.074</td>
<td>5.07</td>
<td>0.05</td>
<td>1.16</td>
<td>7.04</td>
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</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 1996

<table>
<thead>
<tr>
<th>Setu</th>
<th>SUM.CPUE</th>
<th>MEAN_CPAUE</th>
<th>STD.CPUE</th>
<th>MIN.CPUE</th>
<th>MAX.CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.631</td>
<td>40.006</td>
<td>5.49</td>
<td>1.22</td>
<td>2.31</td>
<td>7.36</td>
</tr>
</tbody>
</table>

Catch per unit of effort:
- < 0.00
- 0.00 - 4.99
- 5.00 - 9.99
- 10.00 - 13.99
- > 13.99
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 1997

Catch per unit of effort
- < 3.00
- 3.00 - 4.99
- 5.00 - 5.99
- 6.00 - 6.99
- 7.00 - 7.99
- 8.00 - 9.99
- 10.00 - 11.99
- 12.00 - 13.00
- > 13.00

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUM.CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,988</td>
<td>67,438</td>
<td>6.38</td>
<td>1.96</td>
<td>1.76</td>
<td>9.77</td>
</tr>
</tbody>
</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 1998

<table>
<thead>
<tr>
<th>Seto</th>
<th>SUM_CATCH</th>
<th>MEAN_CPOE</th>
<th>STD_CPOE</th>
<th>MIN_CPOE</th>
<th>MAX_CPOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.762</td>
<td>85.145</td>
<td>6.70</td>
<td>2.14</td>
<td>1.96</td>
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Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 2000

<table>
<thead>
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<th>Set</th>
<th>SUM_CATCH</th>
<th>MEAN_CPOE</th>
<th>STD_CPOE</th>
<th>MIN_CPOE</th>
<th>MAX_CPOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,042</td>
<td>65,132</td>
<td>4.17</td>
<td>0.84</td>
<td>1.38</td>
<td>5.27</td>
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</table>

Catch per unit of effort:
- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 2001

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUM_CATCH</th>
<th>MEAN_CPOE</th>
<th>STD_CPOE</th>
<th>MIN_CPOE</th>
<th>MAX_CPOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.982</td>
<td>26,174</td>
<td>4.01</td>
<td>0.92</td>
<td>1.11</td>
<td>7.74</td>
</tr>
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</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set
- Catch Per Unit of Effort (CPUE) - 2002

Catch per unit of effort

- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUM_CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,917</td>
<td>140,296</td>
<td>5.60</td>
<td>1.14</td>
<td>1.40</td>
<td>12.29</td>
</tr>
</tbody>
</table>

B-9

98
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 2003

<table>
<thead>
<tr>
<th>Sets</th>
<th>SUM_CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>13,211</td>
<td>106,782</td>
<td>3.99</td>
<td>0.69</td>
<td>1.30</td>
<td>9.52</td>
</tr>
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</table>

Catch per unit of effort:
- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00
### Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 2004

<table>
<thead>
<tr>
<th>Set</th>
<th>SUM_CATCH</th>
<th>MEAN_CPE</th>
<th>STD_CPE</th>
<th>MIN_CPE</th>
<th>MAX_CPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>14,712</td>
<td>144,766</td>
<td>4.77</td>
<td>1.91</td>
<td>1.13</td>
<td>7.22</td>
</tr>
</tbody>
</table>

### Catch per unit of effort

- < 3.00
- 3.00 - 4.99
- 5.00 - 5.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00
Number of Bigeye Tuna Caught for Every Thousand Hooks Set
-Catch Per Unit of Effort (CPUE) - 2005

Catch per unit of effort

- < 0.00
- 0.00 - 0.99
- 1.00 - 1.99
- 2.00 - 2.99
- 3.00 - 3.99
- 4.00 - 4.99
- 5.00 - 5.99
- 6.00 - 6.99
- 7.00 - 7.99
- 8.00 - 8.99
- 9.00 - 9.99
- 10.00 - 11.00
- > 11.00

<table>
<thead>
<tr>
<th>Set</th>
<th>SUM_CATCH</th>
<th>MEAN_CPOE</th>
<th>STD_CPOE</th>
<th>MIN_CPOE</th>
<th>MAX_CPOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,309</td>
<td>127,157</td>
<td>4.95</td>
<td>0.57</td>
<td>1.36</td>
<td>5.99</td>
</tr>
</tbody>
</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set - Catch Per Unit of Effort (CPUE) - 2006

Catch per unit of effort
- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00

<table>
<thead>
<tr>
<th>Seto</th>
<th>SUM.CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,000</td>
<td>117,193</td>
<td>3.66</td>
<td>0.98</td>
<td>1.21</td>
<td>7.00</td>
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</table>
Number of Bigeye Tuna Caught for Every Thousand Hooks Set
-Catch Per Unit of Effort (CPUE) -
2007

<table>
<thead>
<tr>
<th>Setu</th>
<th>SUM_CATCH</th>
<th>MEAN_CPUE</th>
<th>STD_CPUE</th>
<th>MIN_CPUE</th>
<th>MAX_CPUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>16,952</td>
<td>157,964</td>
<td>4.35</td>
<td>0.07</td>
<td>1.76</td>
<td>8.53</td>
</tr>
</tbody>
</table>

Catch per unit of effort
- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00
Number of Bigeye Tuna Caught for Every Thousand Hooks Set
- Catch Per Unit of Effort (CPUE) - 2008

Catch per unit of effort

- < 3.00
- 3.00 - 4.99
- 5.00 - 6.99
- 7.00 - 8.99
- 9.00 - 10.99
- 11.00 - 13.00
- > 13.00

Sum | SUM CATCH | MEAN CPUE | STD CPUE | MIN CPUE | MAX CPUE
---|-----------|-----------|----------|----------|----------
16,574 | 150,709 | 4.01 | 1.00 | 1.31 | 6.31
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2000

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2001

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2002

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year
- Confidential cells had sets deployed by fewer than 3 vessels

<table>
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<tr>
<th>Trips</th>
<th>Min Value</th>
<th>Min Value</th>
<th>Min Value</th>
<th>Max Value</th>
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</thead>
<tbody>
<tr>
<td>1,162</td>
<td>30,371,880</td>
<td>299,148</td>
<td>5,278</td>
<td>3,334,682</td>
</tr>
</tbody>
</table>

$ Value of bigeye tuna sold $

- < 150,000
- 150,000 - 499,999
- 500,000 - 999,999
- 1,000,000 - 1,499,999
- 1,500,000 - 2,499,999
- 2,500,000 - 3,600,000
- > 3,500,000
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2003

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.

<table>
<thead>
<tr>
<th>Trips</th>
<th>MEAN Value</th>
<th>MIN Value</th>
<th>MAX Value</th>
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</thead>
<tbody>
<tr>
<td>1,281</td>
<td>2,402,645</td>
<td>592,906</td>
<td>3,757,884</td>
</tr>
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</table>

$ Value of bigeye tuna sold $

- < 150,000
- 150,000 - 499,999
- 500,000 - 999,999
- 1,000,000 - 1,499,999
- 1,500,000 - 2,499,999
- 2,500,000 - 3,500,000
- > 3,500,000
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2004

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2005

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2006

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year
- Confidential cells had sets deployed by fewer than 3 vessels

<table>
<thead>
<tr>
<th>Trips</th>
<th>SUM_Value</th>
<th>MEAN_Value</th>
<th>MIN_Value</th>
<th>MAX_Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,330</td>
<td>3,231,750</td>
<td>1,193,768</td>
<td>1,959</td>
<td>4,064,779</td>
</tr>
</tbody>
</table>

$ Value of bigeye tuna sold$

- < 150,000
- 150,000 - 499,999
- 500,000 - 999,999
- 1,000,000 - 1,499,999
- 1,500,000 - 2,499,999
- 2,500,000 - 3,500,000
- > 3,500,000
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2007

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year.
- Confidential cells had sets deployed by fewer than 3 vessels.
Value in U.S. Dollars of Bigeye Tuna Sold by Hawaii Deep-set Longline Fishery 2008

- Each cell contains the value of all bigeye tuna sold by all vessels for specified year
- Confidential cells had sets deployed by fewer than 3 vessels

<table>
<thead>
<tr>
<th>Trips</th>
<th>MME Value</th>
<th>MEAN Value</th>
<th>MIN Value</th>
<th>MAX Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,311</td>
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<td>1,790,983</td>
<td>48,337</td>
<td>5,514,630</td>
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</table>

$ Value of bigeye tuna sold $

- < 150,000
- 150,000 - 499,999
- 500,000 - 999,999
- 1,000,000 - 1,499,999
- 1,500,000 - 2,499,999
- 2,500,000 - 3,500,000
- > 3,500,000
## Appendix D


<table>
<thead>
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<th></th>
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### Additional Information

- **CPUE** stands for Catch Per Unit Effort.
- The data spans the years from 1994 to 2008, showing trends and changes in CPUE across different rings and cells.
- Each cell (indicated by the grid) contains the CPUE values for the respective years, showcasing variability and patterns over time.

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