A Biological and Social Examination of Opelu (*Decapterus spp.*) Fisheries in West Hawaii, Hawaii Island

A thesis submitted to the Tropical Conservation Biology and Environmental Science Graduate Program at the University of Hawaii at Hilo in Partial Fulfillment of the Requirements for the Degree of Master of Science

May 2008

"Hanau ka Opelu, hanau ke Akule i ke kai la holo"
Born is the Opelu, born is the Akule in the sea and swam
(Kumulipo, translated by Queen Liliuokalani)

Submitted by Blake D McNaughton

Acknowledgements

I would like to express the deepest appreciation to my committee chair, Dr. Craig Severence, whose sense of style should never be questioned.

I would like to thank my committee members, Dr. Jason Turner and David Itano who, although difficult to get in the same place at the same time were always there when I need their help.

In addition, many mahalos to all the fishermen who participated in this study, particularly Brian Fujikawa and Robert Leslie.

Financial support was provided by the Pelagic Fishery Research Program, Honolulu Hawaii.

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By Blake McNaughton

Abstract

This study aimed to fill information gaps in opelu fishery biology and life history as well as catalogue fisher knowledge and the socioeconomics of the opelu fishery in West Hawaii. Field sampling and laboratory analysis examined the biological characteristics of opelu caught by two different fishing methods including size, growth rate, age, sex ratio, maturity, spawning condition, and feeding ecology**.** Fisher interviews contextualized biological data as well as documented fishery data. *Decapterus macarellus* (Cuvier 1833) comprised 98% of the total catch while *Decapterus macrosoma* (Bleeker 1951) composed 2%. The opelu hoopnet fishery catches significantly smaller (mean SL 227.49 ± 28.7mm) and more immature fish (78%) than the handline fishery (284.25 ± 25.7 mm, 7.5% immature). *D. macarellus* are primarily noctural feeders with a diet comprising of 82% crustacean zooplankton by weight. *D. macarellus* exhibited an ontogenetic diet shift indicated by δN^{15} and δC^{13} stable isotope analysis.

Introduction

Decapterus spp., known as opelu in Hawaii, have been an important food and baitfish to Hawaii's residents for as long as the islands have been colonized (Titcomb 1972). Opelu is spoken of in the Hawaiian creation chant, the Kumulipo, which traces the genealogical origin of the Hawaiian people. Opelu is abundant and found close to shore and was therefore easily caught from canoes (Leslie *pers comm*. 2007). In the present day opelu is still especially important to the local population in Hawaii. One can find either fresh or dried opelu for sale in fish markets, grocery stores, and on the side of the road. *Decapterus spp.* are also an essential baitfish for a variety of other fisheries and is the bait of choice for the Hawaiian tuna handline fishery and similar fisheries throughout the Pacific (Wright and Hill 1993, Stobberup and Erzini 2006).

The name opelu encompasses four different species of *Decapterus*, which have been identified in Hawaii (Randall 2006) including *D. macarellus* (Cuvier 1833), *D. macrosoma* (Bleeker 1851)*, D. tabl* (Berry 1968) and *D. muroadsi* (Temminck and Schlegel, 1844). The two most frequently caught species in Hawaii's commercial fishery include *D. macarellus* and *D. macrosoma,* with *D. macarellus* being far more common. In this paper "opelu" will refer to *D. macarellus* unless otherwise specified. *D. macarellus* is a member of the Carangid family and is a common nearshore species with a circumtropical distribution (Froese and Pauly, 2008). Opelu occupy the neritic zone and in Hawaii are usually found at depths between 20 to 200 meters, although they are also sighted offshore, particularly around floating objects.

The opelu fishery is the 2nd most important inshore fishery in Hawaii, just behind akule (*Selar crumenophthalmus*), in terms of both catch and market value. Between 2000 and 2006, Hawaii's commercial fishermen landed approximately 1.6 million lbs (730,000 kg) of opelu worth an estimated 3.3 million dollars. 959,000 lbs (436,000 kg) or 61% of this catch originated in waters on the western, or leeward side of the Island of Hawaii between Keahole point and Milolii (HDAR, 2006). Opelu is found on both the windward and leeward sides of the Hawaiian Islands. However West Hawaii Island's large leeward area has calm, deep water, which supports two different types of opelu fishing, a net fishery that operates during the day and a hook and line fishery, which operates at night.

Despite the commercial, recreational, traditional, and ecological importance of opelu to Hawaii there is a paucity of current scientific information on this species. Many basic parameters of opelu fisheries biology are inconsistent or completely absent. A comprehensive literature survey found that studies by Yamaguchi (1953) and Clarke and Privitera (1995) are the only published works that specifically examine *Decapterus macarellus* biology, whether basic life history or reproduction, respectively. All other references for this species base their assumptions on these two published papers, which were conducted in Hawaii.

This study aimed to fill information gaps in opelu (*Decapterus spp.*) fishery biology and life history as well as catalogue fisher knowledge and the socioeconomics of the opelu fishery in West Hawaii. Field sampling and laboratory analysis examined the biological characteristics of opelu caught by two different fishing methods including size, growth rate, sex ratio, maturity, age, spawning condition, stable isotope ratios, and gut contents**.** Fisher interviews contextualized biological data as well as documented fishery data including number of fishers, fishing types, consumers of opelu, economics of opelu fishing, and distribution paths of the catch.

<u>The Fishery</u>

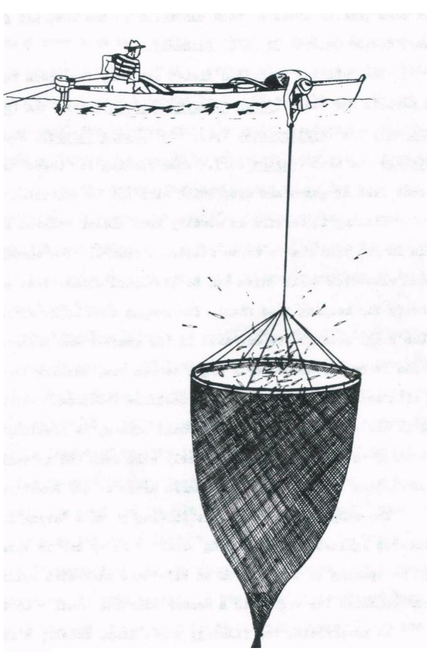


Figure 1: Hoopnet fishing,, courtesy of Yamaguchi 1953.

The Hawaii commercial opelu fishery uses two distinct methods of catching opelu, a daytime hoop-netting method and a nighttime hook and line method. The daytime method involves attracting a school of opelu over a hoopnet/liftnet (Figure 1). Fish are observed through a glass-bottomed box and concentrated under the boat by chumming vegetable material, although some fishers do use animal chum or a mix (Leslie *pers comm*. 2007). This style of fishing originated in Hawaii and has remained largely unchanged since traditional times, other than the advent of motorboats and synthetic nets. Most of the customary netting grounds are located at koas or fish aggregation areas, which are usually associated with a bathymetric feature, such as a submarine ledge or hill. Opelu are usually caught when the current moves in the right direction against these features (Leslie *pers comm*. 2007). Optimal current direction depends on the koa. The location of opelu koas are known through the extensive indigenous knowledge of opelu fishing families along the Kona coast, although potential koas may be identified using a bathymetric map and knowledge of the local currents. Net fishermen typically fish during the winter months but may fish the entire year because the fish respond less to chum during the summer months (Yamaguchi 1953). Many opelu fishermen may also stop fishing for opelu and concentrate on the inshore run of yellowfin tuna during the summer. A good day trip for a net fisherman may yield up to 400 pounds (182 kg) of fish (Leslie *pers comm*. 2007). Hoopnet fishing takes place at 20 to 30 fathoms (40-60 meters) bottom depth.

The night method uses lights to attract plankton, which bring feeding opelu. Fishermen use handlines with small hooks and artificial flies to jig for the fish. The night fishery fishes at greater depths than the net fishery and concentrates on ledges around 50 to 60 fathoms (100-120 meters) bottom depth. A successful trip for a hook and line fisherman may yield up to 250 pounds (114 kg) per night (Fujikawa *pers comm*. 2007). The night fishery operates year round, although they cease fishing three to four nights before and after the full moon. A complete description of the fishing techniques employed by the hoopnet and handline fisheries was previously described by Yamaguchi (1953) and remains up to date.

Decapterus species are important throughout the Pacific as both a food and bait fish. Global catch of *Decapterus* spp. in 2005 was 1,242,606 mt (Froese and Pauly 2008). The Pacific accounted for most of this catch with 1,197,786 mt. China leads the world with 625,837 mt followed by Indonesia at 314,300 mt, and the Philippines with 283,756 mt

(Froese and Pauly 2008). Global and Pacific catches have steadily increased from 1950 while Hawaii's catch has remained relatively constant, averaging about 200,000 pounds

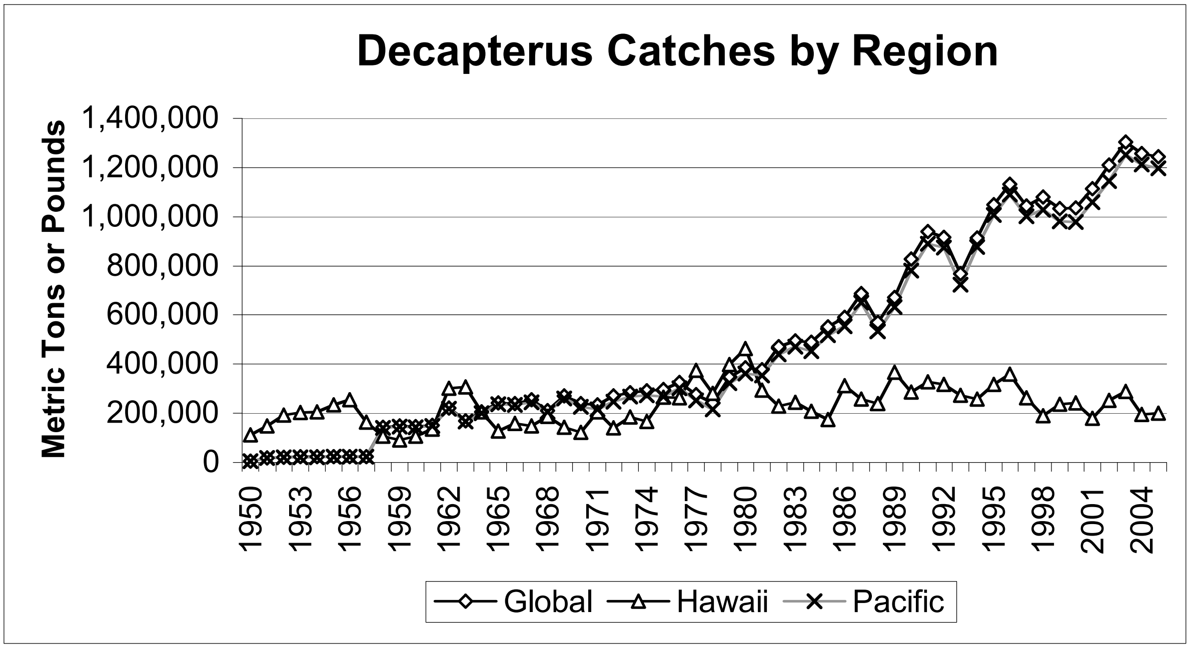


Figure 2: Global and Pacific catches in metric tons, Hawaii catch is expressed in pounds. Latest year is 2005.

(91,000 kg) per year (Figure 2). Honolulu is the primary market in the state for the commercial opelu fishery, although many fish are distributed locally either dried or fresh. Yamaguchi (1953) stated that the net fishery accounted for nearly 70% of the total catch in 1951. In contrast, from 2000 through 2006 the handline fishery in West Hawaii (DAR areas[1] 101 & 121, see figure 3) accounted for 65% of the opelu catch (HDAR 2006).

Average market value in 2006 was 1.93$ per kilogram or 4.26$ per pound (HDAR 2006). Recreational fishers also fish for opelu at koas and Fish Aggregation Devices (FADs) for bait or food. Live and fresh opelu is particularly important for the sportfishing industry and the commercial nearshore tuna fishery (palu-ahi and ika-shibi) for its use as a baitfish. The

[1] Commercial catch is reported by geographical area. Areas 101 & 121 are from Keahole pt. to Milolii.

amount of opelu taken by recreational fishers is unknown, although Hawaii recreational fishing boats certainly outnumber licensed commercial fishermen (Glazier 1999). The Hawaii Marine Recreational Fishing Survey reports few recreational fishermen target opelu as food fish or bait (HMRFS 2008), though this survey may not provide an accurate representation of recreational opelu catch.

Traditionally, Hawaiians were banned from fishing for opelu for the six-month period from January to July. However, the only regulation that is currently enforced is a law forbidding chumming (palu) with animal based material when fishing for opelu (except for hook and line) between the Kiilae-Keokea and Kapua-Kaulanamauna boundaries in West Hawaii, only vegetable palu is allowed (HDAR 2006). The fishermen of West Hawaii initiated this regulation in order to prevent chumming with animal material, which may attract large predators.

In their analysis of the Hawaii Department of Aquatic Resources (HDAR) commercial fisheries dataset, Weng and Sibert (2000) concluded that opelu stocks are in healthy condition due to high growth rates and fecundity. Their population model indicated that opelu were exploited below maximum sustainable yield, were not threatened by the fishery, and that site fidelity was not high enough to promote localized depletion. However, many of Weng and Sibert's (2000) biological parameters were based on the results of Yamaguchi's work in 1953, which contrast in some aspects with Clark and Privitera's 1995 study. Yamaguchi's (1953) laboratory data, from which he determined size at maturity, spawning condition, and sex ratio, was generated from fish sampled entirely from the day net fishery. Clarke and Privitera (1995), however, obtained all of their samples from the nighttime handline fishery. Consequently, neither study adequately sampled both fisheries concurrently and therefore do not provide a representative sample of the entire fishery. These contrasting sampling methods may have skewed Weng and Sibert's (2000) model-based stock assessment. Furthermore, there is currently no length frequency or catch-at age data that could generate age-structured models (Weng and Sibert 2000). Given these inconsistencies, further biological research of the fishery is warranted.

Distribution

The dynamics of opelu movement and site fidelity are largely unknown throughout the world and Hawaii. Hawaii fishermen testify that opelu schools have high site fidelity. This belief is evident by the common practice of net fishermen to always allow some fish to escape in order to facilitate repopulation of the koa. Old-time net fishermen also leave some of the larger fish because they believe these fish teach the smaller fish how to feed on the chum (Leslie pers comm. 2007). Schools of opelu may be found at the same locations day after day, although whether these fish are the same individuals or there is significant movement between aggregations or other areas is unknown. Weng and Sibert's (2000) analysis indicated that opelu is not experiencing localized reduction. This may be because the fishery is not heavily impacting the population or that opelu populations have low site fidelities. A comprehensive literature review revealed no tag and release or tracking studies that have examined the distribution or movements of opelu in Hawaii or elsewhere in the world. There is anecdotal evidence that net fishermen will occasionally catch fish that have hook and line gear caught in their mouths. This evidence implies that the populations have some exchange between net-fished areas at 20-30 fathoms and line fished areas at 50-60 fathoms. Net fishing was shown to yield significantly smaller fish than hook and line, which was thought to be a function of smaller fish caught at shallower depths (Yamaguchi 1953). This may be the natural tendency of opelu, to move to deeper water as they grow. However, this belief may be reinforced simply because the two fishing methods target different sizes of fish due to gear vulnerability.

D. macarellus, which is a pelagic spawner, are not likely to form completely independent reproductive stocks and are therefore not likely to exhibit any discernable genetic difference in Hawaiian waters. Yamaguchi (1953) found no differences in the mean number of anal fin spines or vertebrae between opelu caught in different areas of the state. Number of vertebrae has been found to be an indicator of genetic differences (Iguchi *et al*. 2006) in other species such as nehu (*Stolephorus purpureus*) (Tester and Hiatt 1952) and ayu (*Plecoglossus altivelis*). Furthermore, molecular techniques have not proven to be particularly adept at distinguishing differences in genetic structure of pelagic fish, even in populations that are geographically very widespread (Grewe and Hampton 1998). No geographical heterogeneity, was detected within *D. macarellus* populations using mitochondrial DNA in Indonesian waters over a much larger area than West Hawaii (Arnaud *et al*. 1999). Therefore, molecular techniques will not be used in this study to examine opelu populations in West Hawaii.

Size and Growth

Maximum reported size for *D. macarellus* is 46 cm total length (Froese and Pauly 2008). However, 63% of the fish caught in the Hawaii commercial fishery in 1949-1950 were between 22.5 cm and 28 cm total length (Yamaguchi 1953), which was the last comprehensive examination of mean size. There has been no work done on the early ontogeny of opelu. The minimum size sampled by Yamaguchi (1953) was 45mm standard length. Males and females have not shown significant differences in size although a comprehensive comparison was not found in the literature.

Yamaguchi (1953) generated a growth curve from a sample of 5,500 fish caught in Oahu's waters. Yamaguchi (1953) used the Petersen method to estimate the growth curve and admits "the method of analysis provides no proof that the estimated ages are correct." Weng and Sibert (2000) used Yamaguchi's (1953) length frequency data to fit a von Bertalanffy growth equation for opelu. The growth rate obtained (K=0.075/month) approaches 95% asymptotic length in one to three years. These growth curves have yet to be confirmed with any otolith analysis or monitored growth of specific individuals.

Reproduction

Opelu are heterosexual and iteroparous. Males and females are not sexually dimorphic although they may display some dichromatism. Clarke and Privitera (1995) found sexual dichromatism occurred in populations of akule (*Selar crumenophthalmus*). Currently, sex for *D. macarellus* must be determined through internal examination. Yamaguchi (1953) found an approximate 1 to 1 sex ratio for 713 sampled individuals.

Clarke and Privitera (1995) concluded that spawning occurs from approximately April through August and hypothesized that spawning occurred between dawn and dusk. This seasonal period is reflected by the traditional Hawaiian kapu, which banned opelu fishing from January through July (Kawaharada 2006). Juvenile opelu have been commonly sighted in large schools in offshore areas (Yamaguchi 1953). These juvenile fish may then recruit inshore as they mature to form adult opelu schools, which typically form in mid-waters of deep lagoons, coastal bays, or nearshore areas (Weng & Sibert, 2000). Clarke and Privitera (1995) estimate opelu size at first maturity at 245mm standard length or approximately 18 months old. This is substantially larger than Yamaguchi's estimate of 175mm standard length at maturity. Spawning frequency is still undetermined. Yamaguchi measured oocyte size and found a unimodal distribution, which typically indicates one large spawning event over the spawning season. Clarke and Privitera, however, measured an inconclusive bimodal distribution, which may indicate multiple spawning events or continuous oogenesis.

Feeding

The importance of opelu to the structure and dynamics of the pelagic food web in Hawaii is largely unknown. Opelu is a very common nearshore pelagic fish and can be seen in large schools along leeward and windward coasts. Due to its abundance, *D. macarellus* undoubtedly provides a significant food source for many marine predators. Large, economically important species such as marlin (*M. nigricans*), mahi-mahi (*Coryphaena spp.)*, ono (*Acanthocybium solandri*), and several species of tuna including ahi (*Thunnus obesus, Thunnus albacares*) and aku (*Katsuwomus pelamis*) feed on opelu (Conand 1988, Smith *et al*. 2005, Rizzuto *pers comm.* 2007). Decapterus species are also consumed by many of Hawaii's seabirds including the red-footed booby (*Sula sula*), the brown booby (*Sula leucogaster*), and the threatened wedge-tailed shearwater (*Puffinus pacificus*) (Harrison *et al*. 1983). These predators may target opelu as a food item at different life stages (Graham *et al.* 2007). Small pelagic fishes in Hawaiian waters, such as opelu, may have a substantial influence of populations of these larger pelagic predators.

A limited amount of opelu were sampled for gut content analysis by Yamaguchi (1953). A one time sample of 24 fish from the hook and line fishery and 9 fish from the net fishery indicated that zooplankton species such as hyperiid amphipods, crab megalops, and various fish larvae are the primary food source of adult *D. macarellus* in Hawaiian waters (Yamaguchi, 1953). Although the primary prey groups were significantly different between the two samples, the sample size was too small to draw any definite conclusions. Futhermore, gut content analysis only provides a snapshot of an individual's feeding history and should be augmented with other methods, such as stable isotopes analysis, that may provide a more complete assessment of population feeding ecology.

Social Profile

Fishermen in Hawaii are very knowledgeable about the habitats they work in and the species they catch (Titcomb 1972). Fisher knowledge has been shown to be a critical component in understanding the biology of marine species and the interactions of those species within their marine habitats (Johannes 1981, Johannes *et al.* 2000, Haggan *et al.* 2003). Yamaguchi (1953) was the last published literature that described the social dynamics of the opelu fishery in Hawaii. He described the fishing methods in detail but did not systematically interview fishers on the biology of opelu or report on the sources, distribution, and uses of opelu in fishing communities and Hawaii. This was one of the highest ranked priorities identified at the Pelagic Fisheries Research Program Research Priorities Workshop in Honolulu in November 2005.

Research Objectives

1. Characterize the biological and sociological features of the opelu fishery along the Western coast of the Island of Hawaii.

2. Contrast the biological characteristics of opelu caught by two different fishing methods including length, weight, age, sex ratio, maturity, age, spawning condition, stable isotope ratios, and gut contents.

3. Assess the feeding ecology, trophic position, and diet consistency of opelu caught at various locations, sizes, times of day, and moon phases throughout the year by gut content and stable isotope analysis.

4. Determine and/or verify reproductive characteristics of opelu including spawning frequency, periodicity, and size at maturity.

Methods

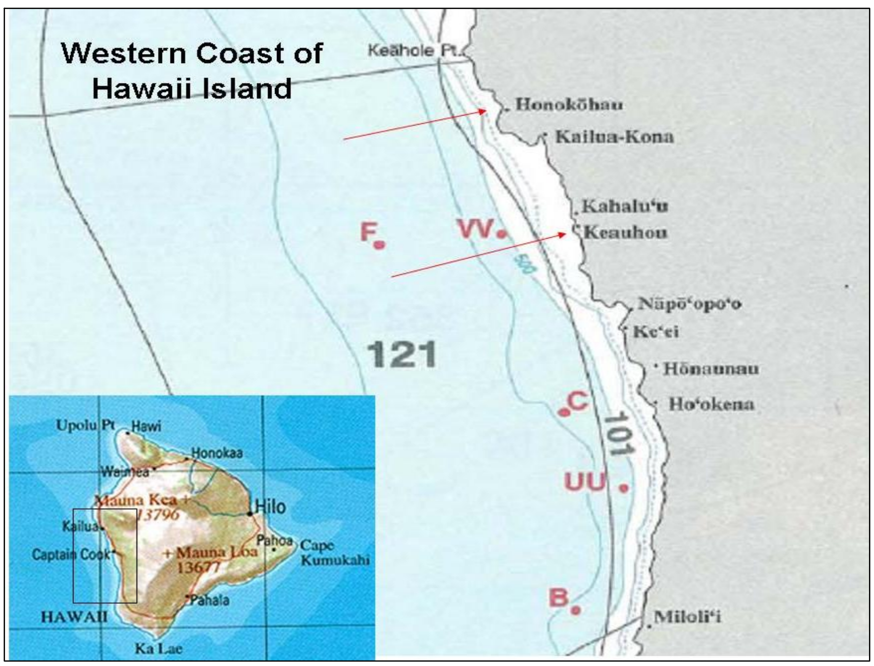


Figure 3: Study site. Arrows indicate Keauhou and Honokohau harbors. Letters indicate State buoys. Number 121 and 101 are State fishery reporting areas. Map Courtesy of HDAR.

Study Site: The study sites or sample locations are located in depths of 20 to 100 fathoms on the Kona coast between Keahole Point and Hookena (HDAR reporting areas 101 & 121). This area, which is approximately 30 miles of coastline, is located on the Western, leeward side of the Island of Hawaii. The ocean here is calm and fishable for the majority of the year and is unquestionably the most important opelu fishery ground in the State. These areas have been traditional opelu fishing grounds for centuries.

Samples were obtained primarily from areas around Honokohau and Keauhou harbors (see Figure 3).

Social Methods: Preliminary written surveys of full-time and part-time opelu fishers were conducted prior to the study period to establish a baseline level of perceptions of seasonal and environmental variability of opelu catches. The preliminary survey served to notify and educate the fishers about the study's scope and aims.

Social survey techniques included written surveys, direct observation, and informal interviews. Written surveys (Appendix 1) were issued systematically and a comprehensive sample of all part-time and full-time opelu fishers along the Kona coast was attempted. The snowball technique, whereby each interviewed fisher identifies potential additional participants, was used to achieve a comprehensive sample. Written surveys documented fisher experience, whether or not they fished full-time, what species they fished for, as well as other questions concerning fisher status. Surveys also addressed fisher knowledge of opelu biology and life history. Questions targeted opelu movements, reproduction, feeding activity, and size distributions of fish through the year and between locations. Lastly, surveys included economic and management oriented questions such as how fish were sold, who bought them and in what condition (fresh or dried), and what stressors (if any) is the opelu fishery under. Whenever possible written surveys were conducted face to face with each fisherman, however in a few instances the surveys were conducted by phone. The author conducted every survey.

Direct observations of fishing techniques were also conducted for both fisheries. Observations identified potential sampling limitations and helped explain sampling trends. A daily log of field notes and informal interviews with fishermen was also recorded.

Biological Methods:

Sampling: Fish were donated or purchased directly at the market rate from participating fishermen for each month in the study period. Fish were sampled over a period of 11 months, encompassing spawning and non-spawning periods, from April 2007 to February 2008. Sample sizes of 20 fish per each method per month were attempted, with a sample periodicity of twice per month (10 fish per method per sample). Fish were randomly chosen from the day's total catch by blindly choosing individuals from different coolers. The fishing location for that day, time of day fished, number of hours fished, pounds of fish caught, depth fished, weather conditions, and any other significant observations were recorded with each sample.

Four different fishermen (two from each fishing type) regularly participated. The number and identity of fishermen were kept constant in order to normalize any natural biological differences between different fishing grounds and different fishing methods. Samples from each fishing method were obtained as close as chronologically possible to each other. The moon phase per each sample was also held as consistent as feasible throughout the sample.

Upon receipt of the fish, each individual was photographed and then bagged in gallon freezer bags and appropriately labeled. Samples were kept on ice until lab processing, which was never more than two days from the catch date.

Lab procedures: Each fish was identified to species using the FAO species identification guide for fishery purposes (Smith-Vaniz 1999). Standard length (SL) and total length (TL) of each specimen was measured to the nearest mm using measuring calipers. Standard length follows Yamaguchi's 1953 protocol and measures opelu from the tip of the snout to the posterior edge of the silver colored spot at the base of the tail. The difference between opelu SL and fork length (FL) is negligible. Total body wet weight was recorded to the nearest .01 g using an Ohaus Explorer Pro scale.

Sex was determined for each fish. For individuals where sex was difficult to ascertain due to extremely small gonad size, the individual was labeled as immature. Gonads were removed and weighed to the nearest .01 g. Whole gonads of all females were fixed in a 5% formalin/saltwater solution. A lateral muscle tissue sample of approximately 20 g was taken and frozen for subsequent stable isotope analysis.

For a random sub-sample of half the fish, the stomach of each fish was removed by separating all other tissue, such as esophageal gangliae, from the stomach and cutting the trachea of each fish just posterior to the gills. The large intestine was then separated from the stomach at the pyloric sphincter and each stomach's wet weight was recorded to the nearest .01 g. The heads of this same subsample were removed and frozen for subsequent otolith removal.

Stomach contents were examined immediately after processing each field sample. Each stomach was cut open and scraped clean. Empty weight of each stomach was then recorded to the nearest .01g. Vegetable and animal/vegetable chum was abundant and readily identifiable in all daytime hoopnet caught fish. Natural stomach contents were separated from vegetable chum before measurement and analysis and chum weight was estimated. Total numbers of prey, digestive state of contents, and percentage composition of wet weight for each prey category were identified using a dissecting scope (Roux and Conand 2000, Bachok *et al.* 2004). Wet weight was used instead of volume because prey items were very small (Hyslop 1980). Prey categories included copepoda, amphipodae, euphausiidae, mysidae, gastropoda, crab megalopa, annelida, icthyoplankton and other, which was usually plant material. Because of the size of the gut contents it was very difficult to identify items more precisely than the taxonomic order. Prey items in each category were blotted dry and weighed to the nearest .01 g. Digestive state was rated on a scale of one to three with: 1 = undigested, with color and readily identifiable; 2 = being digested, little color is evident (white), digestive masses formed; 3 = completely digested, no/little soft tissue, only exoskeletons remain, digestive mass is now black. In the cases where only exoskeletons remained this study used eyeballs as an indicator of the number of individuals consumed (Hyslop 1980).

A small subsample of each female gonad was examined to determine the maturity of each fish according to the maturity stages set by (Clarke and Privitera 1995). Oocytes < .2mm were considered immature. Oocytes > .2mm in diameter or in which vitellogenesis was visually complete (fully yolked) were considered mature. Subsamples of different areas of the gonad were checked on preliminary samples to determine if gonadal origin has any effect on oocyte diameter. There were no conclusive differences, however to ensure consistency all subsamples were taken from the middle section of the right gonad. Oocytes were teased apart on a glass slide and measured under a compound microscope with an ocular micrometer. 20 ova-diameters were measured for immature fish to determine the largest measured oocyte. 100 ova-diameters were measured for fish with oocytes over .20mm. Only mature oocytes were measured to determine the size distribution of these mature gonads. Each gonad was thoroughly checked for hydrated oocytes and for any evidence of spawning. Spawning may be indicated by disorganized ovarian septa with conspicuous spaces, residual early stage atretic oocytes, and brown bodies (Nagahama 1983).

Both left and right saggital otoliths were removed from each fish by cutting dorso-ventrally through the center of the skull. Otoliths were then removed, rinsed in de-ionized water and stored to dry. Once dry, otoliths were weighed to the nearest .0001 mg using a Sarorius CP2P microscale and their length was measured to the nearest .1mm using digital calipers. Individual otolith condition was noted as some otoliths had pieces that broke. 100 fish were then randomly selected and the otolith that was in the best condition, whether right or left, was ground to a cross-section for aging (Folkvorda *et al.* 2000). Otoliths were mounted onto glass slides using crystal bond and ground on a Crystal Master 8 grinder using 1000b grit waterproof sandpaper to a thickness less than .1 mm. Length of the otolith cross-section, corresponding to the width of the entire otolith measured through the centrum, was measured to the nearest .001mm using an ocular micrometer. "Daily" increments were then counted for 80 otoliths in replicates of 3 using a compound microscope at varying magnification (40x-200x). Replicate counts that differed by ± 10% from each other were discarded (Feet *et al.* 2002).

Stable isotope analysis of carbon 13/12 ratios and nitrogen 15/14 ratios was conducted on dorsal muscle samples of all fish to determine isotopic structure in the musculature. Approximately 1 mg of lateral muscle tissue was prepared for stable isotope analysis using standard protocols, where samples are dried (70°C, 48 h), finely ground (< 250 mm), and packaged into tin capsules (5 x 9 mm) for processing. Samples were weighed to the nearest .001 mg on a Sarorius CP2P microscale before being packaged. Samples were then sealed under a vacuum and combusted at a predetermined temperature setting for 15 h using a Thermo Delta V Advantage isotope ratio mass spectrometer (IRMS). Approximately 10% of the samples were run in duplicate to determine any differences within the samples and between uses of the mass spectrometer. Standard deviations between values of δC^{13} and δN^{15} replicates were minimal at .117‰ and .129‰ respectively.

Biological Results

A total of 31 samples were taken in West Hawaii over a period of 11 months from April 2007 to February 2008. There was a gap in sampling in July 2007 due to highly irregular catches.

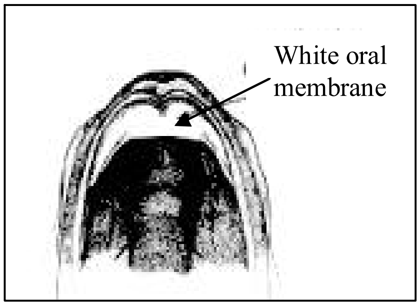


Figure 4: The white oral valve membrane of *D. macarellus.* (Froese and Pauly 2008)

304 total fish were sampled from 5 different fishermen. Two different species were sampled, *Decapterus macarellus* and *Decapterus macrosoma. D. macarellus* was by far the more abundant species in the nearshore opelu fishery comprising 98% of the total sampled catch. 6 out of 304 sampled fish were identified as *D. macrosoma*. All *D. macrosoma* samples were caught by the day-hoopnet fishery. *D. macrosoma* catch amounted to 2% of the total catch and 4% of net caught fish. These two species are most easily differentiated by the distinctively white oral valve membrane at the symphysis of the upper jaw in *D. macarellus* (Figure 4). *D. macrosoma* has a clear oral valve membrane.

Opelu caught at night by handline are significantly larger than fish caught in the day by hoopnet (Table 1). Handline caught fish also had larger Gonad to Somatic Index (GSI) values. There were no significant differences in standard length or weight of fish caught by the same method in different locations, primarily Honokohau and Keauhou. All values shown in Table 1 are significantly different with p values < .0001 using a Welch's modified t-test.

Table 1: Handline caught vs. Net caught Opelu (*D. macarellus*)	
Handline	**Net**
N = 156	N = 142
Mean Weight = 304.42 ± 56.4 g	Mean Weight = 151.10 ± 92.6 g
Mean Standard Length = 284.25 ± 25.7 mm	Mean Standard Length = 227.49 ± 28.7mm
Mean Total length = 312.25 ± 27.7 mm	Mean Total length = 249.07± 30.7mm
Mean Gonad weight = 1.89598 ± .84 g	Mean Gonad weight = 0.40401± 2.12 g
Mean Gonad to Somatic Index = 0.5946 ± .34 %	Mean Gonad to Somatic Index = 0.1915 ± .61 %

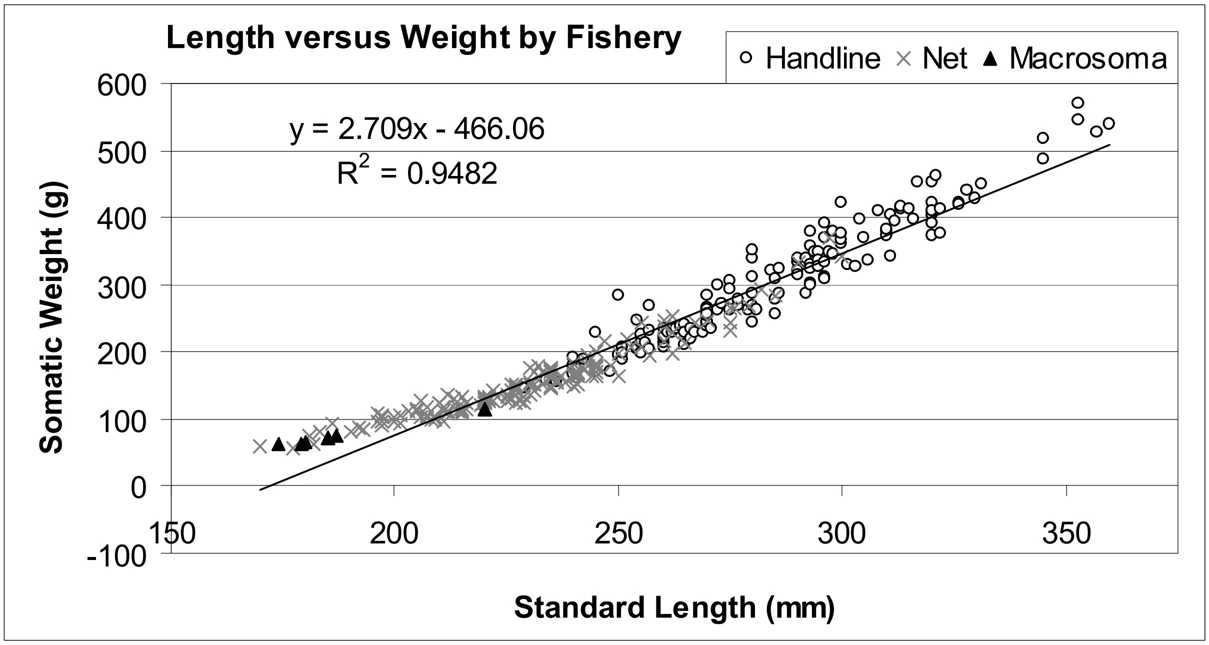


Figure 5: Standard length versus somatic weight linear regression.

D. macarellus standard lengths ranged from 170-360mm and somatic weights ranged from 58-570g. Linear regression analysis (Figure 5) between standard length and weight for all sampled fish showed an R^2 value of .948 and is defined by the equation: Weight (g)= (2.709*Standard Length (mm)) – 466.06. Figure 5 clearly shows the differences between lengths and weights of the handline and net caught fish. One should note the sampled *Decapterus macrosoma* at the bottom of the linear regression. Mean *D. macrosoma* weight was 77.64 ± 20.4 g, which was significantly smaller ($p<0.0001$) from the mean net caught *D. macarellus* weight of 151.10 ± 92.6g. Mean *D. macrosoma* standard length was also

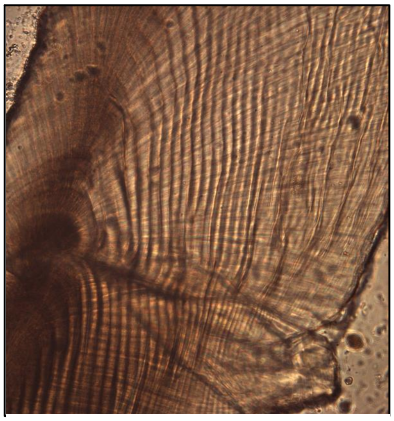


Figure 6: Growth rings at 40x.

significantly smaller ($p<0.0001$) measuring 187.5 ± 16.5 mm versus net caught *D. macarellus* at 227.49± 28.7 mm.

Otolith increment counts of *D. macarellus* were assumed to be accumulated daily. The thickness of growth increments from the centrum toward the outer portion of the otolith changed in a consistent manner for all specimens. The first 10-20 increments were pronounced and thick, measuring up to 25ųm wide (Figure 7). The increments gradually decreased in thickness, measuring less than 1ųm wide on the outer portion of the otolith (Figure 6). The larger the otolith, the more difficult it was to accurately count the growth increments because of the high number and close proximity of the increments.

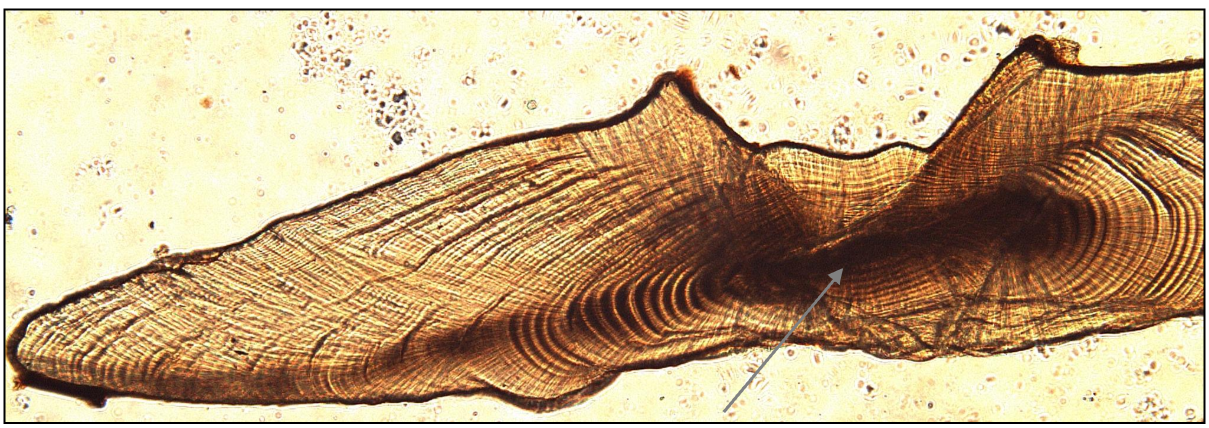


Figure 7: Otolith cross-section magnified at 4x. The centrum is denoted by the arrow.

Otolith length was proportional to standard length throughout the size range of sampled fish (R^2=.79, N=271) although no fish under 170mm were sampled. Otolith width and otolith weight also had significant R^2 values when compared to standard length using linear regression analysis (R^2=.55 and R^2=.59 respectively). This information shows that otolith increments do increase over time and may be used for age determination. However, the periodicity of these increments may vary through different life stages and may therefore result in biased increment counts (Beamish and McFarlane 1983).

Daily otolith increment counts of 66 fish from a range of sizes were compared to otolith weight, length, and width using linear regressions. R^2 values measured .89, .70, and .81 respectively and all p values equaled 0. While all of these measurements were found to have significant relationships with increment counts, otolith weight was found to have the highest R^2 value (.89). Otolith weight should therefore be considered the best proxy for aging otoliths of *D. macarellus* and is defined by the linear regression formula: Otolith Weight (mg)= (0.0370* # of increments) + 0.4992. Measured otolith weights, lengths, and widths ranged from 2.27-12.61 mg, 3.8-7.3 mm, and 1.8-2.8 mm respectively.

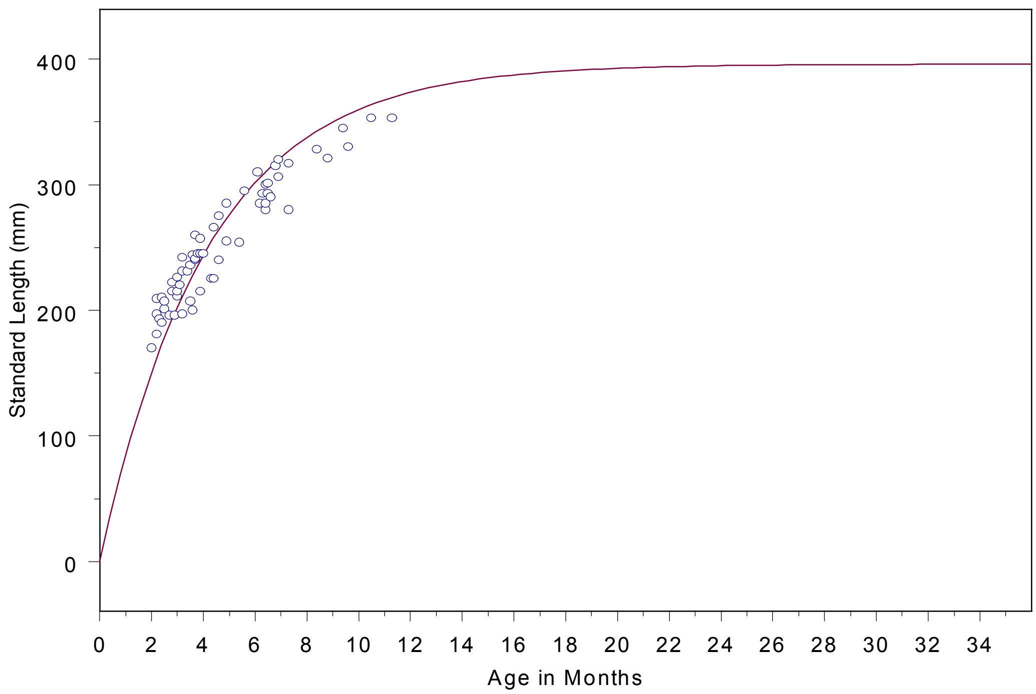
A von Bertalanffy growth curve for *D. macarellus* (Figure 8) was fit to the growth increment count data (N=66). Length at infinity was estimated by using the SL of the largest sampled fish (360mm) plus 10% or 396mm. The growth rate constant K was estimated using a non-linear least squares regression with quadratic bootstrapping (SPSS 16.0). Table 2 shows the equation and analysis outputs. Fish ages by month (mean otolith increment count/30) ranged from 2 to 12 months old. Mean age for net caught fish was 93 days ± 21 compared to handline caught fish, which were significantly older (t test, $p<0.0001$) averaging 190 days ± 60.

Table 2: Growth equation values. t = time.

Function	**Equation**	**K**	**R^2**
von Bertalanffy	L(t)=L infinity*(1-(exp(-K*t))	.236/month	.78

There were no significant size differences between males and females nor was there any sexual dimorphism or sexual dichromatism in freshly caught fish. Immature fish with extremely small gonads that were difficult to classify by sex (N=13) were not used in the analysis. A chi-squared test ($p<0.0001$) showed that the handline fishery caught significantly more males (64%) than the hoopnet fishery (41%). Linear regression analysis showed a significant correlation between somatic size and gonad weight ($R^2 =.36$, $p<0.0001$).

Figure 8: von Bertalanffy Growth Curve



Therefore to normalize this correlation for further analysis, a Gonad to Somatic Index (GSI) was generated using gonad free body weight and is shown through time in Figure 9. All GSI values rose in the summer months from April through August, confirming the recognized spawning period for *Decapterus macarellus* (Clarke and Privitera, 1995). 75% of mature females were sampled between April and August. However This study found several opelu with mature gonads in September (N=2), October (N=2), November (N=3), December (1), and one very large individual in late February.

Birth dates of *D. macarellus* aged by otolith analysis (N=66) were calculated by subtracting each individual's age in days from their date of capture. Birth date in this study means that otolith increments are forming and does not necessarily dictate the spawning date as there might be a period of time between spawning and otolith increment formation. Frequency of fish born in each month is shown in figure 10.

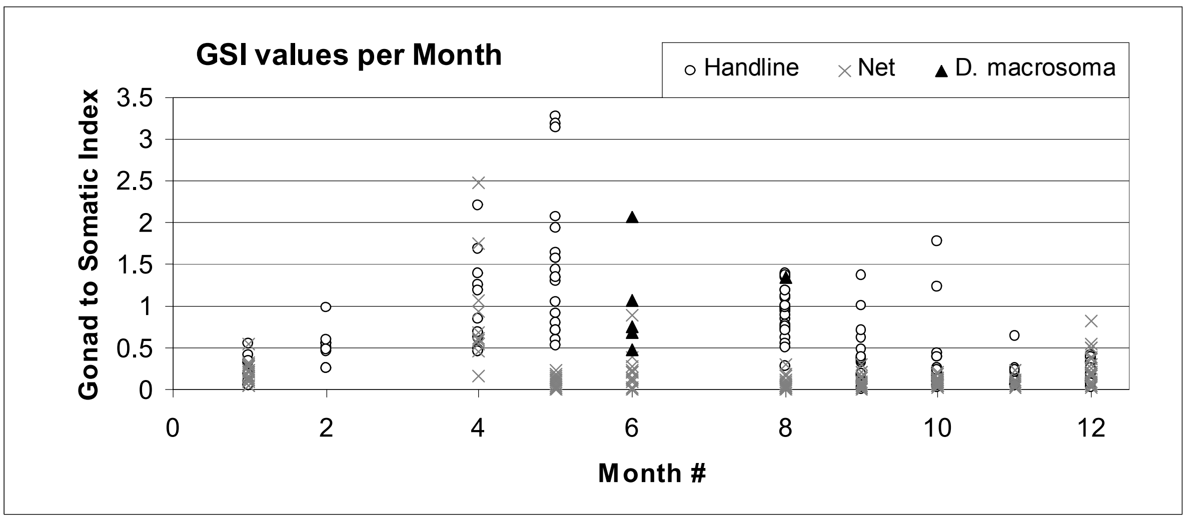


Figure 9: Gonad to Somatic Index (GSI) by month**.** Sample period runs from April 2007 to February 2008.

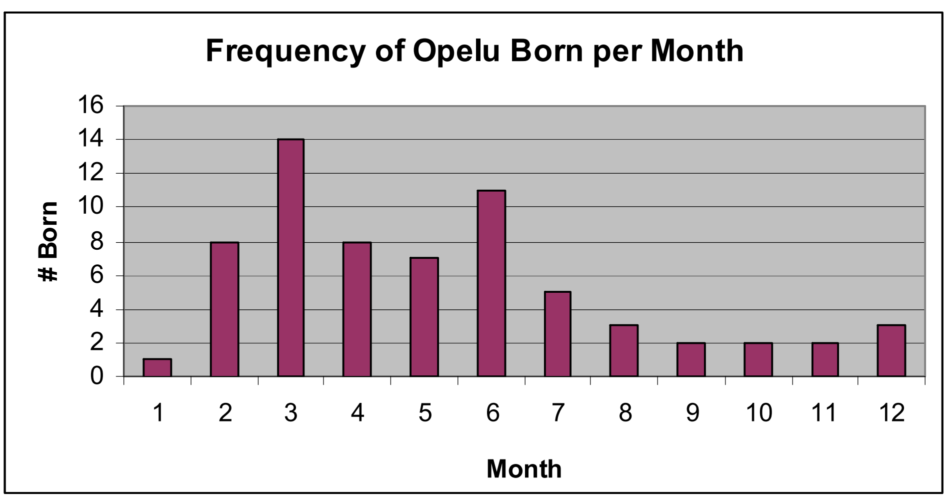


Figure 10: Shows the frequency of fish calculated to be born in each month

The present study found no gonads with hydrated oocytes and no evidence of spawning. Size at earliest maturity, based on oocyte size (immature <.20mm, mature >.20mm) (Clarke and Privitera 1995), for female *D. macarellus* was 257mm standard length (N=138)(Figure 11). Males are assumed to mature at approximately the same size. For fish longer than 257mm, 46% of the examined females were mature, 54% had immature gonads. Only three immature samples were collected in June, July or August when oocytes are typically mature and those three were sampled after August 15th. Within the spawning season (April to Sept.), 89% of fish larger than 257mm SL were mature (N=46). Length at earliest maturity for *D. macrosoma* was much smaller at 197mm (N=3) (Figure 11).

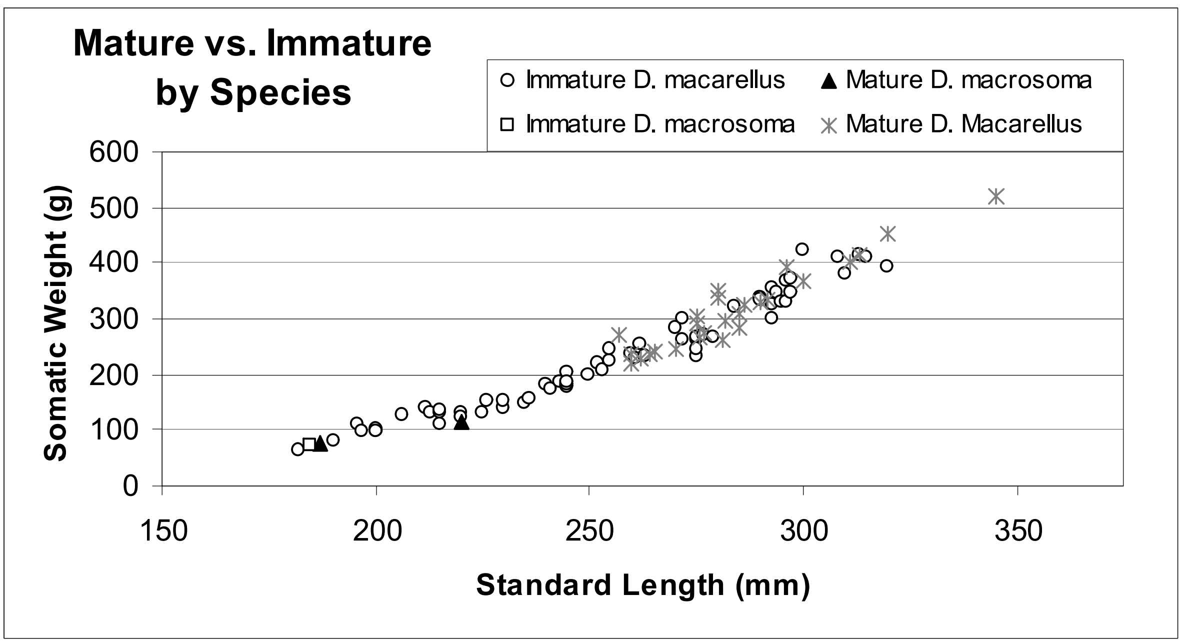


Figure 11: Note this figure only includes females and includes individuals examined in spawning season and off-season.

For mature females (N=27) 100 ova-diameters were measured. The largest ova-diameter found was .572mm. No individual had oocytes with bimodal size-frequency distributions where the modal distributions did not significantly overlap. The majority of fish had unimodal distribution regardless of mean oocyte diameter. Figure 12 shows 8 different oocyte size frequency distributions.

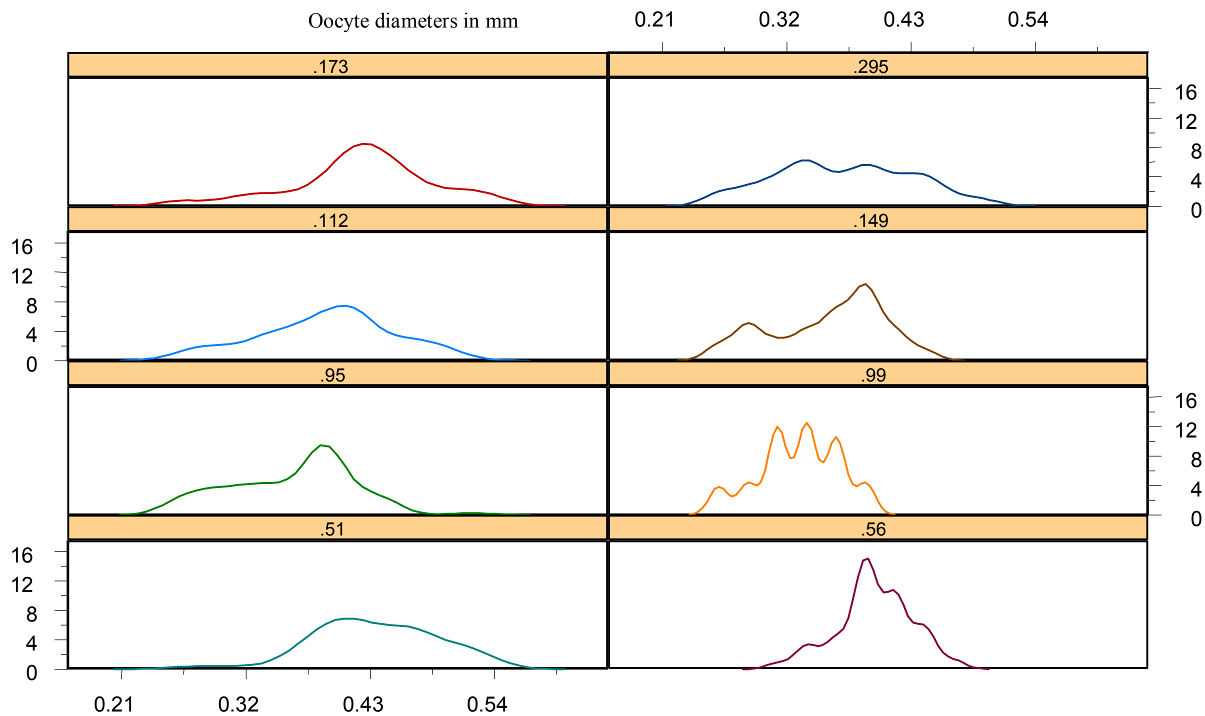


Figure 12: Oocyte size frequencies of 100 mature oocytes for 8 separate samples. Left and right axes denote size frequency. Mean size of each sample is shown in the bar at the top of each graph.

Gut Content Analysis (GCA) was conducted on 159 fish, 74 handline caught fish and 85 net caught fish. Standard length and weight were both correlated with gut content weight ($p<0.0001$) by linear regression analysis. Therefore a Gut to Somatic Index was calculated for further analysis using gut free body weight (BW) and the wet weight of gut contents (GT). The Gut to Somatic Index formula used was (GT/BW)*100. There were significant differences in the gut contents between daytime-net caught fish and nighttime-handline caught fish (Table 3). Net caught fish were filled with chum that was typically oatmeal and ground fish. When natural gut contents were separated from this chum, net caught fish had more empty stomachs, less gut contents on average, and less digested stomach contents (Table 3). An Analysis of Variance using a Tukey multiple comparison test for different size groups of fish showed these feeding parameters were consistent between handline caught and net caught fish.

Table 3: Gut Content Analysis: Summary of net caught gut versus handline caught				
Test	**Test Type**	**Net Mean**	**Handline Mean**	**P value**
% Empty	Summary	49% out of 85	15% out of 74	NA
Gut/somatic index	t-test	0.0352 ± .096	0.1016 ± .31	.0849
Fullness index	Chi squared	4.37 ± .71	3.14 ± 1.27	**0**
Digestion index	Chi squared	1.15 ± .57	2.10 ± .56	**0**

Dietary components were expressed as a percentage of numerical composition (Cn), percentage of gravimetric composition (Cw), and percentage of frequency of occurrence (F). An Index of Relative Importance (IRI) for each fishery type was calculated to express the most important food item using the formula: IRI = (Cn + Cw) * F (Pinkas *et al.* 1971). Handline caught fish primarily feed on crab megalops and euphausiid shrimp. Net caught fish feed on copepods and small gastropods (Table 4). Linear regression analysis of night caught fish show larger fish consume more euphausiids and ichthyoplankton compared to other food groups, with P values approaching significance (p = 0.078, p=0.077 respectively). Crab megalops were consistently fed upon throughout *D. macarellus* size range. Values for the percentage of numerical composition (Cn), percentage of gravimetric composition (Cw) and percentage of frequency of occurrence (F) closely correlated with the IRI values and so are not summarized here.

Table 4: Average Index of Relative Importance (IRI). Bold values are significant. N=159									
	Icthyo-plankton	Copepoda	Amphipoda	Crab megalops	Euphausiidae	Mysidacea	Gastropoda	Annelida	Other
Hand line	38.7	35.7	16.6	**9308**	**2502**	0.2	35.9	26.2	0.1
Net	3.8	**7634**	10.6	28.1	75.1	0.2	**1631**	0.0	41.3

Raw δC^{13} values ranged from -16.1‰ to -17.7‰. Stable isotope analysis of tissue samples taken from all fish (N=304) show δC^{13} values increase with size and fit a linear regression (R^2=.40, P< 0.0001): note the low *D. macrosoma* values (Figure 13). A Welch's t-test confirmed a significant difference (p< 0.0001) in mean δC^{13} value between immature (SL<245mm) and mature (SL≥245mm) *D. macarellus* (Table 5). SL lengths for maturity were based on Clarke and Privatera's data. Linear regression analysis of δC^{13} values versus standard length for each catch method showed handline sampled fish had a very low R^2 value (0.057) compared to net sampled fish (R^2 =0.4935). P values were significant for both these tests (p-values <.008). Because δC^{13} values were correlated with fish size, they were normalized using the equation; $\delta C^{13*} = \delta C^{13} - (a*SL)$; where δC^{13*} = the adjusted value, δC^{13} = the raw value, a = regression coefficient (.0057), SL = standard length. Adjusted δC^{13*} values were used in all tests except the regressions comparing size and maturity to the raw stable isotope values (*in italics* Table 5). δC^{13} values also differed between species and months of comparison. δC^{13} values did not have significant differences between moon phases, sex, or catch location for the entire sample or when grouped by catch method (Table 5).

δN^{15} values did not show significant trends in any category although values were highly variable among individuals, ranging from 6.04‰ to 14.3‰ (Table 5). δN^{15} values were log transformed to normalize data distribution for statistical analysis.

δC^{13} and δN^{15} values did not show a significant relationship with each other by linear or non-linear regression analysis (R^2 values < .006) (Figure 14). δC^{13} and δN^{15} values, when grouped by maturity, did show visible differences between maturity types (Figure 14). *D. macarellus* caught by the two different catch methods did not have significantly different stable isotope values (Table 5) in contrast to the very different perceived gut contents by each catch method (Table 4).

Table 5: Stable isotopes δC^{13} and δN^{15} summary statistics. Ratio values in ‰

Test	δC^{13}: R^2 and Mean ± SD Values	δN^{15}: R^2 and Mean± SD Values	P Values
t-test Catch Method	Net =-18.17 ± .19 Handline =-18.19 ± .41	Net =7.67± .81 Handline =7.57 ± 1.2	N^{15} =.41 C^{13}=.59
Linear regression standard length	R^2 = 0.393	R^2 = 0.00119	N^{15} = .55 **C^{13} = 0**
Linear regression somatic weight	R^2 = 0.295	R^2 = 0.00226	N^{15} = .41 **C^{13} = 0**
t-test location	Honokohau = -18.16 ± .33 Keauhou= -18.20 ± .36	Honokohau = 7.62 ± 1.1 Keauhou= 7.56 ± .90	N^{15} =.53 C^{13} = .27
t-test male vs female	Females= -16.53 ± .34 Males= -16.59 ± .32	Females=7.65 ± .93 Males=7.63 ± 1.1	N^{15} =.92 C^{13}=.10
Anova Moon phase	NA	NA	N^{15}= .28 C^{13}=.43
Mann-Whitney U test species	D. macarellus = -18.17 ± .26 D. macrosoma = -18.77 ± .51	Macarellus = 7.632 ± .12 Macrosoma = 7.039 ± .09	N^{15} = .10* **C^{13} =. 033**
t-test Maturity	Mature = -16.55 ± .18 Immature = -16.84 ± .36	Mature = 7.71 ± .85 Immature = 7.56 ± 1.18	N^{15} = .19 **C^{13} = 0**

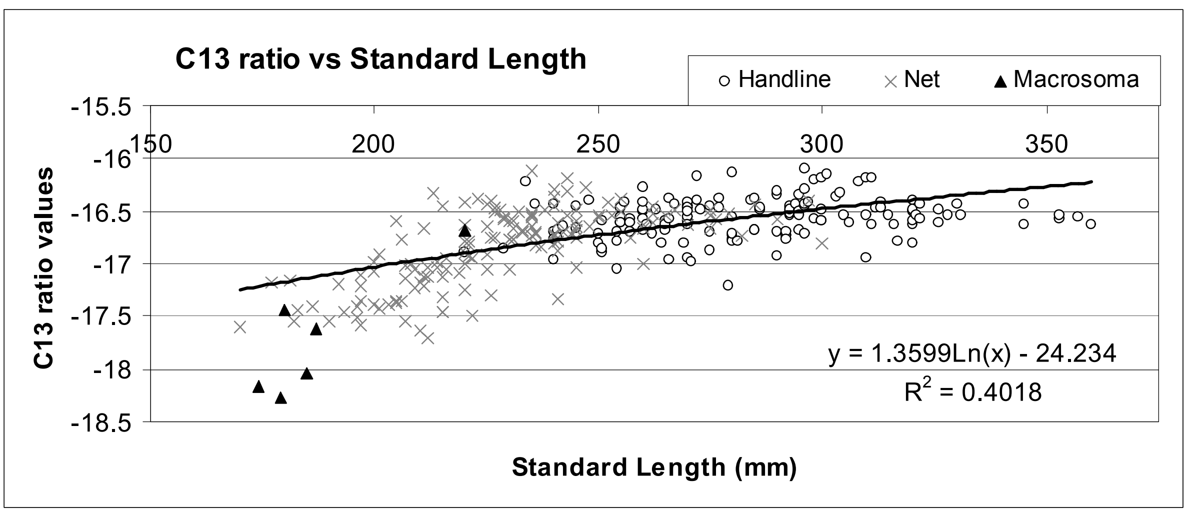


Figure 13: Best-fit line was a natural log of δC^{13} ratio values as shown.

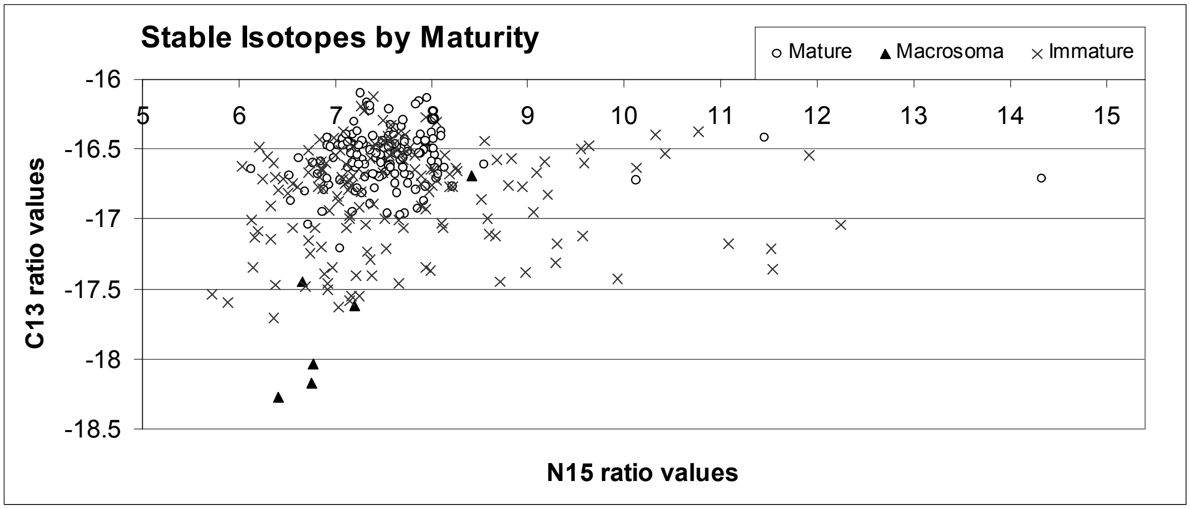


Figure 14: Shows stable isotope ratio values of nitrogen versus carbon grouped by maturity. Fish greater than 245mm SL were considered mature (Clarke and Privitera 1995).

An Analysis of Variance using a Tukey multiple comparison test compared adjusted δC^{13} values from month to month and showed values varied significantly ($P<0.0001$). No such difference was detected for δN^{15} values. However, sample sizes per month per method did not exceed 20 and may therefore not be representative of opelu population parameters from month to month. Linear regression analysis of log transformed Gonad to Somatic Index (GSI) values to both length adjusted δC^{13} values and log transformed δN^{15} Values showed significant p-values (0, .002 respectively) although R^2 squared values were low and do not show a strong correlation (0.072, 0.032 respectively).

Social Profile Results

10 opelu fishermen from West Hawaii were interviewed using predetermined survey questions (Appendix 1). An estimated 12-14 fishermen regularly fish for opelu in the whole of West Hawaii including Milolii, Kawaihae, and North Kohala. This estimate is based on informal interviews and the number of West Hawaii fishers reporting catches to the State of Hawaii. This social profile captured a large percentage (72-83%) of the likely universe of

opelu fishermen in West Hawaii. 9 of 10 interviewees were fulltime fishermen and 6 of 10 fished for opelu the whole year. No fishermen had been fishing for opelu less than 5 years and 80% had been opelu fishing for more than 10 years.

4 of 10 interviewees fished using hoopnets during the day while the rest (6 of 10) were night fishers using handlines. This ratio echoes the fishery as a whole as approximately 60% of the fishermen in the State use handlines versus 40% using hoopnets (HDAR 2006). Fishermen all fished 4 or more times per week and usually fished for 5 to 6 hours per trip depending on the bite and the weather. On good months a trip would yield 135 to 180kgs but low periods could yield only 9 to 18kgs per trip.

All fishers agreed that smaller fish (less than .25 kg) are caught in June, July, and August, particularly in the net fishery, and the number of net fishers operating during this period is smaller as well. Larger fish (more than .25kg) are caught in the winter months. Fish with mature eggs were commonly reported from April through August though several fishermen reported finding mature eggs throughout the year. 80% of interviewees reported that fish spawn twice per spawning season.

8 out of 10 fishermen said that the night, handline fishery catches larger fish that are separate from the small fish caught in the day. However, all net fishermen reported occasionally catching opelu with handline gear in their mouths. 100% of the surveys indicated that opelu migrate from shallow water in the day to deeper water to feed at night. All night fishers agreed that there was a pronounced size gradient at night as one moved from 20 fathoms bottom depth (smaller fish) to 50 and up to 70 fathoms bottom depth where the fish were larger. Several fishers stated that one could occasionally see small opelu in the deeper water as well but they were not regularly caught. The primary reason given by

interviewees for this gradient was predator avoidance. Fishermen identified several predators seen feeding on opelu schools including multiple species of shark, aha (*Tylosurus crocodilus*), kamanu (*Elagatis bipinnulata*), omilu (*Caranx melampygus*), ulua (*Caranx ignoblis*), kahala (*seriola* sp.), ono (*Acanthocybium solandri*), kawakawa (*Euthynnus affinis*), keokeo (*auxis* sp.), aku (*Katsuwonus pelamis*), ahi (*Thunnus* sp.), mahimahi (*Coryphaena hippurus*), kaku (*sphyraena* sp.), roudi (*Promethichthys prometheus*), and nai'a (*Stenella* sp.).

Only one fisherman, with 40 years experience, reported catching a different species of opelu (*D. macrosoma*). This was the same fisherman who caught the *D. macrosoma* specimens.

All interviewed fishers sold their entire catch rather than distributing it among various families or communities. 8 of 10 interviewees sold their entire catch locally. 2 of 10 shipped 70 to 80% of their catch to the Honolulu fish market. 40% of the fishermen dried the opelu and 60% sold their catch fresh. Identified outlets for the fish included wholesalers Suisan and the Hilo fish company, markets such as KTA and SureSave, as well as individuals for food and bait. All fishermen identified the ahi (*Thunnus* sp.) fishery as the main consumer of opelu as baitfish. All fishers agreed that the opelu fishery is inherently limited by market size rather than opelu population size.

Discussion

The present study is the first to identify *D. macrosoma* as a species caught by the opelu fishery in Hawaii. However, catch rates of *D. macrosoma* (2% of the total catch) may be skewed due to low sample size (N=6). *D. macrosoma* is difficult to distinguish from *D. macarellus* because there are no obvious physical differences. Only 1 of 4 interviewed net fishermen recognized the separate species despite more than 80 years of experience between the four. No handline fishermen recognized descriptions of *D. macrosoma* or remembered catching the species. Fishermen reported *D. macrosoma* to be caught in areas with sandy bottoms. *D. macrosoma* does have a more uniform silver color, which may provide camouflage in sandy areas. Fishermen also reported that *D. macrosoma* is typically caught during the winter months, however our samples were captured in June and August. This conflicting information implies a resident population that is only occasionally caught.

In his 1953 study Yamaguchi found that hoopnet caught fish standard length (SL) averaged 220mm SL while handline caught fish averaged 240mm SL. Yamaguchi's (1953) hoopnet average closely approximates the present study's data at 227mm SL, however our handline estimate is significantly larger than Yamaguchi's (1953) at 284mm SL. Additionally the present study sampled only 4 out of 148 handline caught fish under 240mm SL (Yamaguchi's average). The largest opelu sampled by Yamaguchi (1953) was 330mm SL while our largest *D. macarellus* sample was 360mm SL. Size differences may be an indication of the average size of handline caught opelu in Oahu, where Yamaguchi's (1953) samples originated from, versus opelu caught in West Hawaii. Average differences are likely due to the failure to identify any *D. macrosoma* in Yamaguchi's samples because at that time there was confusion in taxonomy of the *Decapterus* genus. Regardless of these results, both studies found that the opelu handline fishery is catching significantly larger fish in terms of weight and length. Sample sizes in the present study were too small to reflect monthly differences in mean size and are not presented here though results do correlate with fisher testimony.

Gear vulnerability may be contributing to the fish size stratification by fishery type. Net fishermen indicate that they occasionally see larger opelu that feed on the chum with the smaller fish, particularly during the summer months. Oftentimes when the fishermen begin to pull their net the larger fish swim out and the fishermen capture the smaller sized fish. This phenomenon is occasional, however and does not likely account for most of the variability between fisheries.

The present study found that within the spawning season, 100% of female *D. macarellus* greater than 257mm SL were mature. Clarke and Privitera (1995) reported that 81% of females greater than 245mm SL were mature within the spawning season. In contrast, Yamaguchi found mature fish as small as 175mm SL. This study found that *D. macrosoma* matures at a much smaller size; size at first maturity for this study was 197mm SL, which is consistent with Tiews *et al.* (1971) report that *D. macrosoma* matures at 210mm total length. The presence of *D. macrosoma* in the net fishery catch supports Clarke and Privitera's (1995) conclusion that there were some *D. macrosoma* in Yamaguchi's (1953) laboratory samples. Using 245mm SL as the length at maturity, 78% of the net fishery catch is estimated to be immature compared to 7.5% of the handline fishery catch.

Sex ratio of fish caught within Hawaiian waters also appears to be stratified by method of capture. The handline fishery appears to catch significantly more males (64%) versus the hoopnet fishery (41%). This stratification is not size-driven as mean fish size was not significantly different between sexes within each method of capture. Clarke and Privitera (1995) also noted that handline catches contained few females. Eight of their sixteen samples contained less than 20% females. Yamaguchi did not sex any handline caught fish, however he found that net catch, during the spawning season, was comprised mostly of males

(55%). The present study did not find the same trends within each fishery during spawning season and off-season. Sex ratios remained consistent throughout the entire sampling period. However, all evidence indicates that few mature spawning females are caught by either fishery, which may be critical for the sustainability of the commercial opelu fishery. Whether spawning females are not vulnerable to the current fishing methods or migrate to a separate location is undetermined.

Spawning season was found to be consistent with previous reports (Yamaguchi 1953, Clarke and Privitera 1995) although fish with mature gonads were found throughout the year. 2 of 10 interviewed fishermen also reported that they occasionally found mature eggs in individuals throughout the year. This evidence indicates a protracted spawning season where *D. macarellus* may have limited spawning activity over most of the year. The small dataset collected for *D. macrosoma* in the present study correlates with Conand's (1988) report that *D. macrosoma* spawns in the southern hemisphere's summer months (Nov-February) in New Caledonia.

Decapterus macarellus gonads were indicative of a synchronous by groups ovary type with a group of similarly sized oocytes that are immature and an advanced group of oocytes that were mature (Nagahama 1983). Clarke and Privitera (1995) did report several occurrences of sampled ovaries with mature oocyte size frequency distributions that were bimodal but admitted that the data was inconclusive. Groups of mature oocytes that are bimodal may indicate batch spawning in which females have several cycles of egg maturation and spawning within a single season (Lisovenko and Andrianov 1991). However none of the mature gonads sampled in this study were truly bimodal. Yamaguchi (1953) also reported a unimodal oocyte size distribution. 80% of interviewed fishermen reported that opelu probably spawn twice per season, however when questioned further, no one could provide any anecdotal evidence of this conclusion. This data suggests that *D. macarellus* spawns once per spawning season.

Diel reproductive periodicity of Carangidae is poorly known but appears to be highly variable between species, as some species spawn during the day, while others are believed to spawn at night (McBride *et al.* 2002.). Existing data for the genus *Decapterus* shows variable spawning periods with reported nocturnal spawning for *D. russelli* and *D. macrosoma* (Tiews *et al.* 1971). *Decapterus punctatus* was reported to spawn at dusk (McBride *et al.* 2002.) and diurnal spawning was proposed for *D. macarellus* (Clarke and Privitera 1995). This study did not find any individuals with hydrated eggs at any time despite sampling from both the net and handline fisheries. One net fisherman reported seeing spawning behavior early one morning in June, "the fish were swimming up and eggs were coming out". This report suggests that *D. macarellus* spawns near dawn in the same areas where the net fishery operates. However, fishermen do not appear to be catching many fish that are in the process of spawning. Histological examination by Clarke and Privitera (1994) showed postovulatory follicles present in only 3 of 35 females. The absence of any ovaries with indications of spawning or any individuals with hydrated oocytes in the present study suggests that mature females may be spawning at a separate area from either fishery grounds. Several interviewed fishermen reported that opelu might move far offshore to spawn. Further research of *D. macarellus* spawning location and diel periodicity is warranted.

Growth rates of *D. macarellus* were determined from otolith increment readings which were assumed to be daily and laid down in a consistent manner throughout the life of the fish. *D. punctatus* has been shown to have daily growth rings and the case may be true with *D. macarellus* as well (Hales 1987). Estimated growth rates from this study indicate that *D. macarellus* reaches 95% asymptotic length in one to two years. Growth rate from the Von Bertalanffy (K=0.236/month) growth model are comparable to K-values reported for *Decapterus punctatus* and *Selar crumenopthalmus* (Kawamoto 1973, Hales 1987). In addition, slower growth rates reported for *D. macrosoma* (Tiews *et al.* 1971) and *D. macarellus* (Yamaguchi's 1953) were both based on length-frequency data, which assumes fish of equal length to be birth cohorts. This method is useful for synchronous spawners, however accurate growth rates are difficult to measure in a species with a protracted spawning period because cohorts may be born days, weeks, and months apart and result in a population that is highly variable in size (MacDonald 1987). *D. macarellus* may mature in as little as 5 to 6 months according to the present study's calculated growth rates. These growth rates correspond with fisher testimony, that opelu entering the fishery as "cigar" opelu (less than 150mm TL) are able to spawn in 3 months. Since opelu appear to be preyed upon by a variety of large and abundant marine organisms, high mortality rates may necessitate a fast growth rate and relatively early maturation (Harrison et al. 1983, Uchida *et al.* 1982, Dalzell and Penaflor 1989, Smith *et al*. 2005).

Gut content analysis indicates that day caught fish have significantly different gut contents than night caught fish. Night caught fish had more stomach contents and a far smaller percentage of empty stomachs. These results show that *D. macarellus* feed primarily at night. Evidence of nighttime feeding has been demonstrated in small plankton feeders such as anchovies and sprats (*Stolephorus* sp., *Spratelloides* sp.)(Milton *et al.* 1990), and akule (*Selar crumenophthalmus*) (Kawamoto 1973). Night caught gut contents were also more digested than day caught, indicating that sampled fish were not simply feeding on macroplankton attracted to the fishing lights. Therefore gut content analysis for night caught fish shows a true representation of feeding preferences. Day caught fish, however, were typically full of the chum used to attract the fish into the net. Planktonic organisms were mixed in with the chum and appeared to be consumed along with the chum. Day caught gut contents were frequently undigested, particularly the copepods and gastropods, the two most important food items for net caught fish. These observations reinforce the conclusion that *D. macarellus* are nocturnal feeders. Fisher testimony strongly supports this evidence. *D. macrosoma* had similar results, although no fish were sampled at night and sample size was too small to draw any definitive conclusions.

Opelu diet contained only pelagic animals with no mineral material or benthic animals. The present study found *D. macarellus* rely on crustacean mesoplankton, particularly crab larvae. Yamaguchi (1953) found similar results with limited samples and concluded that crustacean plankton form the dominant portion of opelu's food. Randall (1967) found that *D. macarellus* in the West Indies feed primarily on pteropods, though that data was from only two day-caught specimens. Akule (*Selar crumenophthalmus*) also depend on crustacean plankton as a food source although larger fish were primarily piscivorous (Roux and Conand, 2000). The present study found that *D. macarellus* food habits echoed this trend. Sampled ichthyoplankton were fairly large and could likely only be consumed by larger fish.

All interviewed fishers testified that opelu migrate at dusk into deeper water to feed at night. Opelu then migrate to shallower water in the day, presumably to avoid predation. Benoit-Bird and Au (2006) showed that during the day in Hawaii high densities of mesoplankton merge into a single layer in water layers at 400m depth or deeper. These mesoplankton populations, comprised primarily of myctophid fish and euphausiid shrimp, then migrate vertically and horizontally toward the shore to bottom depths in which the opelu handline fishery operates (Benoit-Bird and Au 2006). Opelu populations may be exploiting these zooplankton migrations for feeding.

Nitrogen and carbon stable isotope ratio values were comparable to similar sized fish in other marine systems (Thomas and Cahoon 1993, Hansson *et al.* 1997). δC^{13} values exhibited a positive relationship with standard length of opelu although smaller sized fish showed a much stronger linear relationship between size and δC^{13} value than larger fish. In addition mature fish showed significantly different mean δC^{13} values than immature fish. This may be caused by ontogenetic shifts in the diets of the smaller net caught fish. Larger fish typically prey on higher trophic levels than smaller fish and ontogenetic diet shifts are well known for many species of fish (McCormick 1998, Jennings *et al.* 2002). This study showed differences between δC^{13} greater than 1‰, which typically indicate a change in trophic level feeding (Peterson and Fry 1987). There was no such relationship between fish length and δN^{15}, as one would expect if larger fish were feeding at a higher trophic level. Nitrogen isotope ratios typically increase by 3‰ to 5‰ per trophic level (Peterson and Fry 1987). δN^{15} values ranged from 6.04‰ to 14.3‰, which does indicate a diet composed of multiple trophic levels. One explanation for this disparity between δN^{15} and δC^{13} carbon may be due to differences in metabolic fractionation of carbon isotopes with size due to environmental variables such as colder water. Fisher testimony does indicate that larger fish prefer deeper water and that fat content in opelu rises during the winter months, which

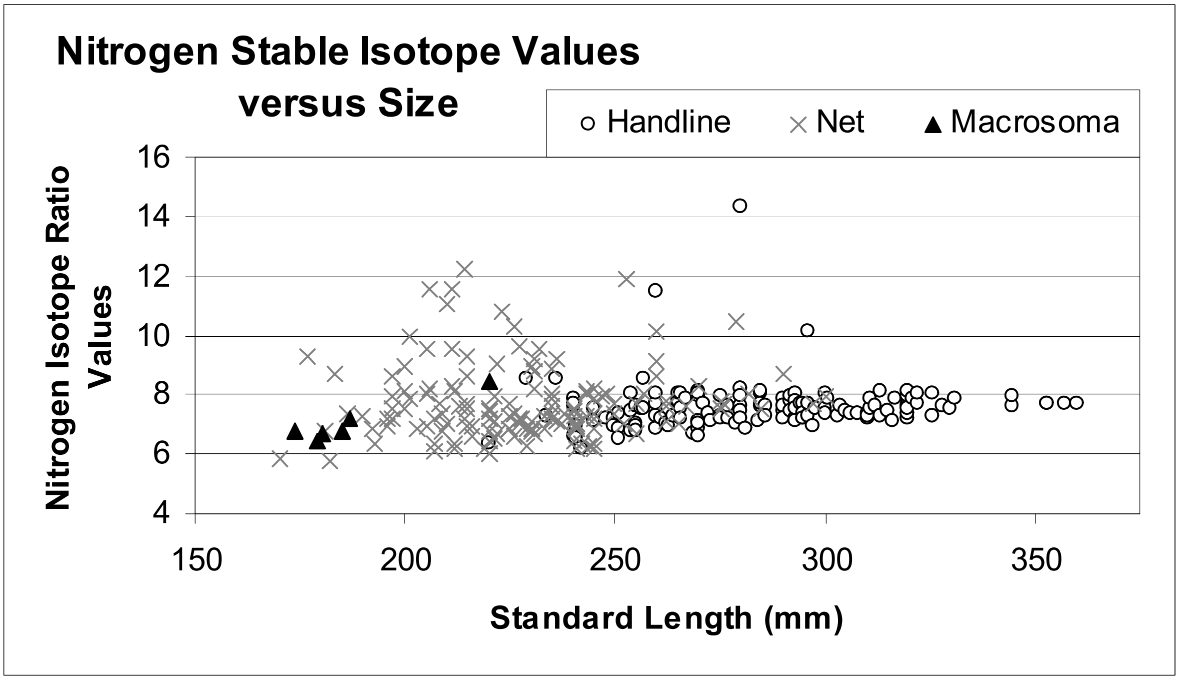


Figure 15: Shows **δN[15]** values separated by catch method. Note the high variability of values of smaller sized fish.

correlates with calculated δC^{13} values. "You can taste the fat," one fisherman was quoted. Muscle lipid content levels have been shown to influence carbon fractionation in fish (Jennings *et al.* 2002). A more likely explanation is that as fish grow larger, their diet's nitrogen isotope levels are too variable to reveal a relationship with size while carbon isotope levels increase with larger prey. Why opelu may be exhibiting a dietary shift with size or maturity is unknown although there are many possible reasons that the author will not speculate on.

δN^{15} values were variable across all size ranges although smaller, immature fish show much more variability in δN^{15} (Figure 15). Net caught fish may be exhibiting highly variable δN^{15} values due to eating chum that is often oatmeal mixed with marlin or fish tissue, which is a high trophic level predator. Handline caught fish also show some extreme δN^{15} values (Figure 15) although the data is much less variable. If the net fishery is changing opelu population stable isotope signatures by consistently feeding chum to opelu, this may have ramifications on opelu survivorship.

A definitive conclusion as to whether these variable δN^{15} values are caused by life history or feeding parameters is difficult to make. An examination of immature opelu diet caught at night in shallow water may help to clarify if opelu exhibit a change in diet and what is causing that shift. Isotopic signatures did show a degree of overlap between catch methods, which confirms that day caught and night caught opelu may be feeding upon similar food sources and are not likely to be completely separate populations.

Significant positive relationships between GSI values and stable isotope values suggest that when opelu are spawning, or have large gonads, their diet changes to incorporate enriched stable nitrogen and carbon isotopes, presumably due to high energetic costs. This change in isotope values may also be a result of seasonal abundance of prey items although analysis of variance comparing isotope values between sample months showed a difference in carbon but not a significant difference in stable nitrogen values.

δC^{13} values did differ significantly between *D. macrosoma* and *D. macarellus* of similar size groups although δN^{15} values did not differ significantly between species according to Mann-Whitney U tests (P=0.10). However this may be due to the low sample size (N=6) of *D. macrosoma*. Further investigation of these species' differences is warranted and may clarify how the present study's stable isotope values should be interpreted.

Social profiling of the opelu fishery in Hawaii showed that opelu fishermen have a wealth of knowledge about opelu biology and ecology. Most fishermen had been fishing for opelu for more than ten years and are deeply committed to the fishery. Interviews showed that catch is sold and distributed locally, mainly through markets and wholesalers, with some fish being shipped to the fish markets in Honolulu. Several fishermen reported that the markets would import opelu from the Philippines if catches were small. Fishermen who sun-dried their catch expressed special concern that the Federal Food and Drug Association was implementing stricter regulations about sun-drying fish despite the fact that opelu had been dried in that manner for centuries (Titcomb 1972). If sun-drying is outlawed, fishermen will have to dry their catch in convection ovens whose operation often negates the price benefit of drying the fish.

50% of fishers thought that there were fewer opelu now compared to 10 years ago. "The schools are just smaller" one fisher stated. The fishers that declared opelu stocks were declining cited many reasons including coastal development and pollution. However, half the interviewed fishermen stated that they're just as many opelu now as ten years ago and were much more concerned for the future of opelu fishing. "Its hard work without a lot of glory," as one fisherman put it. Many of the interviewees had been fishing for a long time and were close to retiring. As these fishermen leave the fishery there may be no one willing to replace them, which could mean more *Decapterus spp*. will be imported from countries such as the Philippines.

Conclusion

Ecosystem based fishery management is rapidly being adopted by institutions charged with stewardship of the marine environment due to increased recognition of the significant direct and collateral impacts that fishing imposes on marine ecosystems (Browman *et al*. 2004). However, an ecosystem approach to fisheries management requires, at a minimum, a basic knowledge of population dynamics and trophic interactions of the major species in each ecosystem. Biological characteristics are becoming increasingly important in the management of many commercially important fish stocks (Misund 1997), especially when calibrating or creating population models. This study has helped to build that biological knowledge of *D. macarellus* and West Hawaii's opelu fisheries by addressing several notable gaps in our knowledge of opelu biology.

Results from this work include the following, 1) A current dataset of biological characteristics for both types of commercial opelu fishing in West Hawaii, 2) A current assessment of the important social parameters that influence those opelu fisheries and a social profile of currently active West Hawaii opelu fishermen 3) New information on the feeding and trophic ecology of opelu and 4) Insight into the life history information of *D. macarellus* and *D. macrosoma*. These results improve our knowledge of crucial biological parameters, particularly in regard to opelu movements, diet, growth, and length frequency to improve modeling efforts and stock assessments.

By examining opelu caught by the two major fisheries, this study has documented a distinction between the fishery's catch. These fisheries are catching different life history groups and the fisheries should be researched and managed accordingly. Management recommendations could include limiting the net fishery during the primary spawning period, because the fishery is targeting juvenile fish and the net fishery typically slows during this period anyway. Stable isotope analysis coupled with fisher testimony indicate that night caught fish and day caught fish are not from separate populations, although there may be a relationship between fish size and bottom depth. Data on growth rates of *D. macarellus* shows that opelu may be a much faster growing species than previously thought. A tagging study that researched *D. macarellus* marked otolith growth or an enclosed growth experiment would be an ideal form of validation for this data. These calculated growth rates, indicative of a highly productive species, support Weng and Sibert's (2000) conclusions, based on population models of Hawaii's opelu fishery, that the opelu fisheries are lightly exploited.

Spawning frequency of opelu is most likely once per season. Opelu did show a protracted spawning season with a few individuals having ripe eggs throughout the year. The opelu fisheries are catching few mature females, which may contribute to the sustainability of the fishery. This evidence also indicates that mature females may be moving out of the fishery grounds to an unknown location during spawning periods.

Data on trophic interactions and feeding are also necessary in creating any population model. This study showed that opelu feed primarily at night and rely heavily upon crustacean zooplankton as their primary food source. Opelu may be migrating towards deeper water to take advantage of zooplankton diel movements. Opelu predators are varied and may rely heavily upon opelu as an abundant food source, which force opelu to move into shallower water during daylight hours. The role of these movements in the life of the migrators and the ecological consequences of these patterns are poorly understood, particularly for animals larger than plankton (Benoit-Bird and Au 2006), although small pelagic fish such as opelu have been shown to exert a major control on the trophic dynamics of ecosystems (Cury *et al*. 2000). A tagging study would also help to elucidate opelu movements and would confirm whether fish move between the net fishery grounds and the handline fishery.

The present study has also helped to characterize opelu fishers of West Hawaii and their concerns. Many opelu fishermen voiced concern about the future of the fishery for various reasons though few advocated restricted fishing as a management tool. These fishers are committed to this fishery, however, and understand the habitat they work in. The knowledge and cooperation of these fishers will be vital to any future management efforts in West Hawaii and the State.

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Appendix 1

Opelu Social Survey for Fishermen

This survey is meant to document your knowledge about opelu fishing, the life cycles and biology of opelu, and your experiences while fishing. It is better to not answer a question than to answer it incompletely. If at any time you feel uncomfortable answering any of the questions please let the interviewer know.

Area(s) Usually Fished

Fishing Type (Net, Line, Day or Night)

How long have you been fishing for Opelu? (0-5 years), (6-10 years), (11-20 years), (more than 20 years).

Do you consider yourself a full-time or part-time fisherman?

Do you regularly fish for other kinds of fish? If yes, what kinds?

*What months of the year do you fish for Opelu?

How often a week do you fish for opelu? (1),(2),(3),(4 or more)

How long a day or night (in hours) do you typically fish for?(1-2),(3-4),(5-6),(7 or more)

How many fish (in lbs) do you usually catch per trip in a good month? Bad month?

*What months of the year do you catch larger fish on average (over ½ pound)?

*What months of the year do you catch smaller fish on average?

Are most of the fish in a school the same general size? (yes , no)

*Do notice any months of the year when the Opelu eggs drop?

*Do notice any months of the year when the Opelu are spawning (eggs in the water or the school showing spawning behavior)?

Do individual opelu spawn multiple times or only once per year? Why?

Do you know of any areas where spawning fish are caught or seen more frequently? If yes why do you think that is?

Are there any areas where you catch larger or smaller fish (inshore, offshore, Fads)?

Do you think the fish caught at night are from the same schools as the fish that are caught in the day?

Have you ever seen opelu in areas where they are not usually fished for (eg. 1000 fathoms? If yes, what sizes were they? (1/2 pound, pound, over a pound)

*Is there any time of year where opelu are more abundant at the State or private buoys? If yes, what size are they usually? (1/2 pound, pound, over a pound)

Do you see different sized fish feeding together?

Do you ever see parasites on or in the opelu and if so what do they look like? (include periodicity)

What other kinds of fish do you see when you are catching Opelu? Are they feeding on the opelu?

Do you ever catch any other kinds of opelu (red tail, big, etc.)? If so please describe what they look like, where, and when you caught them.

Do you sell all your catch?   If not, why?

Do you sell your catch fresh or dried? (all fresh, all dried, quarter fresh ¾ dried; half and half: ¾ fresh quarter dried or does it depend)

Who do you sell to (fresh and dried)? Stores, Wholesalers, Individuals for Bait, Individuals for Food.

If you sell to a variety of people then what are the percentages to each group? (round to nearest 5%)

When you sell for bait, what are the fishermen usually fishing for?

(For Net fishermen) What kind of Palu do you usually use?(vegetable, animal, mixed)
Have you ever used or heard of Opae'ula as palu for opelu fishing?(yes , no)

Are there any indications that there will be a good or bad year for opelu fishing (eg. when the mango trees are full the ahi will have a big run or lots of rain, etc.)

Is opelu fishing harder now than ten years ago? If yes or no, for what reason?

Why don't more people commercially fish for opelu?

Do you have any concerns for the future of opelu fishing?

Do you have any recommendations to make opelu fishing better in the future?

Any Other Comments (anything you think should have been asked but was not)