E Hui Pū: A collaborative approach to understand climate change impacts on traditional Hawaiian ʻōpelu (*Decapterus macarellus*, mackerel scad) aggregation sites in South Kona, Hawaiʻi

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Introduction

In the past, traditional Hawaiian fishing communities managed natural resources through cultural practices that emphasized sustainability and accounted for the need for adaptation. Observing seasonal patterns in fish spawning, migration, and behavior allowed for both proactive and responsive management actions, including seasonal closures. Master fishers rotated the harvest of key marine species to allow for the maintenance of healthy and abundant stocks. These careful management practices were instilled in lawaiʻa (fishermen) as cultural values that were passed down in families over many generations. In the Kapalilua region of South Kona on Hawaiʻi Island, this was especially true for the ʻōpelu (*Decapterus macarellus*, mackerel scad) fishery where, traditional management and harvest practices have survived into the 21st century.

Increased changes in harvest practices, including off-season extraction, coupled with documented, environmental changes have resulted in a noted shift in ʻōpelu behavior and potential spawning periods. Communities who remain dependent on the health of this culturally and economically critical marine resource have been activated by these observed changes and have developed collaborative spaces for ʻōpelu research in their traditional fishing boundaries. In close partnership with the state's marine resource management agency, the Department of Land & Natural Resources- Division of Aquatic Resources (DLNR-DAR), community members of Hoʻokena seek to better understand and document these changes in order to create responsive management actions can be made by DLNR-DAR.

Since 2017, members of the community-based organization Kamaʻāina United to Protect ʻĀina – Friends of Hoʻokena Beach Park (KUPA) as well as other fishers have partnered with Conservation International Hawaiʻi (CI-Hawaiʻi) to co-develop and carry out a community-driven ʻōpelu research project to gather key biological and behavioral data within the traditional fishing boundaries of the Hoʻokena community (Image 1). By combining indigenous knowledge on traditional management practices and western science data collection techniques, an integrated methodology for understanding potential changes in ʻōpelu spawning and behavior was utilized. These shifts in ʻōpelu behavior may be a result of environmental changes. In this study we focused on monitoring ocean temperature and salinity, to establish a data baseline. The data presented below are a product of a multi-partner collaboration that leveraged support from the University of Hawaiʻi's Pacific Islands Climate Adaptation Science Center (PI-CASC) to provide additional data collection resources in the 2019 calendar year. With seed funding from CI-

Hawaiʻi and additional support from the County of Hawaiʻi Research & Development office, the Hawaiʻi Tourism Authority, and the Office of Hawaiian Affairs, this ongoing collaboration was well-positioned to capitalize on the support from PI- CASC.

Members of the Hoʻokena community have long been committed to the work of conserving precious natural resources in order to perpetuate the unique cultural traditions in what is one of the few remaining Hawaiian fishing villages across the islands. Over the last several decades, family and community members in Hoʻokena have organized themselves and developed significant organizational capacity to execute successful partnerships with the County and State of Hawaiʻi to steward coastal and nearshore resources from the ahupuaʻa of Kēōkea to Kalāhiki, South Kona. This PI-CASC collaboration is a valuable contribution to the ongoing and future work of ensuring ocean abundance in Hawaiʻi.

Climate change impacts on the health and abundance of fisheries in Hawaiʻi have been realized with emerging research efforts seeking to document perceived and real impacts. Among those impacts are increased variability in coastal and oceanic conditions (temperature, currents, upwelling, etc.), resulting in increased variability in marine populations and their behaviors (Hays *et al.*, 2005; Doney *et al.*, 2011). Natural resource managers must incorporate management strategies to adapt to the uncertainty that climate change is evoking onto rapidly changing marine ecosystems (Ainsworth *et al.*, 2011; Lawler *et al.*, 2010). However, managers are often stretched too thin, covering an array of physical areas and issues and often, do not have the means to address challenges of this scale (Lawler *et al.*, 2010). Developing adaptive strategies is perhaps the most important technique managers can use to address these changes. Climate change impacts on Hawaiian fisheries health and resilience are being realized across Hawaiʻi. DLNR- DAR have adopted an initiative of effectively managing 30% of its coastlines by the year 2030 (“30 X 30”) (HDAR 30, 2019).

The initiative states:

> “Effective management” includes a suite of adaptive management approaches balancing sustainable use, restoration, and conservation measures such as community-based management, time and area closures for fisheries replenishment, reasonable laws

to encourage sustainable fishing practices, and effective enforcement, combined with systematized monitoring to assess effectiveness.

To accomplish this mission, DLNR-DAR will have to rely on practitioners, non- profit groups, NGOs, universities and a number of other sources to successfully reach their goal. A straightforward link can be made from the 30 X 30 initiative and the South Kona community driven sustainable management objectives. As a key species culturally, ʻōpelu makes a great candidate for this type of management but as a coastal pelagic, the need for increased understanding may be much larger.

Small, coastal pelagic fishes are sensitive to many environmental changes, especially in early life stages (Faleiro *et al.*, 2016; Ma *et al.*, 2019). Warming marine environments can cause shifts in spawning grounds, stock size and survival rates. Shifts in these populations due to increased fishing pressure or environmental changes can also have a marked effect on trophic balance. Coastal pelagic fishes have an important, intermediary trophic role, as prey to larger pelagic species and predator to macro-zooplankton, creating an important transfer of nutrients between trophic levels and from near shore and pelagic environments (Cury *et al.*, 2000; Santos *et al.* 2007; Weng and Sibert, 2014). Trophic changes affect not only the marine organisms, but also humans as declines in fisheries have implications for food security, economic livelihoods and in many cases, cultural ties surrounding the collection, sharing and eating of particular organisms (Bindell *et al.*, in press; Titcomb, 1972). *Decapterus macarellus,* though not well known, are caught throughout the world as a food and bait fish (Froese and Pauly, 2019).

In Hawaiʻi, *Decapterus macarellus*, commonly known as ʻōpelu or mackerel scad, play an important role in the Hawaiian marine ecosystem as a human food source, culturally important fish, economically important commercially, as a desired fish, a bait fish, as well as, an important component of larger predatory fish's diet (Ma *et al.*, 2019; McNaughton, 2008; Duarte and Garcia, 2004). Large predatory fish include all billfishes, bottom fishes, barracuda, ulua/pāpio (trevally), mahi-mahi, rainbow runner, various tunas, dolphins and several species of sea birds (Harrison, 1983; Status, 2004; Yamaguchi, 1953). ʻŌpelu are amongst the top caught species in Hawaiʻi's inshore/ coral reef fishery (McNaughton, 2008; Weng and Sibert, 2004; Status, 2004).

In recent years, fishers along the southwest coast of Hawaiʻi Island, have noted significant changes in the ʻōpelu, fishery including declines in catch, altered fish behavior and migrations (Alani, *pers comm.* 2019; McNaughton, 2008). ʻŌpelu fishery decline has significant impact on the ability of South Kona coastal, indigenous communities to implement traditional, Hawaiian management practices to hānai koʻa (feed and maintain ʻōpelu aggregation sites), which, supports long-term fishery health and abundance. The South Kona region of Hawaiʻi Island comprises most of the fishing effort and over half of the reported commercial catch of ʻōpelu in the main Hawaiian Islands (Clarke and Privitera, 1995; HDAR, 2019; McNaughton, 2008; Weng and Sibert, 2000). This fishery has a long cultural history in Hawaiʻi and is a major food source, as well as, an important component of traditional food sharing for Hawaiian communities (Hawaiʻi, 2009; McNaughton, 2008; Titcomb, 1972; Yamaguchi, 1953). Traditional management of ʻōpelu is implemented through kapu or closed seasons which, supports the sustainability of the fishery (McNaughton, 2008; Kaleohano, 1976; Titcomb, 1972; Yamaguchi, 1953).

ʻŌpelu fishers of South Kona use traditional practices of hānai (to care for, feed) to attract ʻōpelu to koʻa (natural fish aggregation sites). They travel by waʻa (outrigger canoe) with small outboard motor to known koʻa to feed palu (mix of pumpkin, papaya, and other fruits or vegetables). Locations of these koʻa are passed down through the generations. During a self-imposed closed season (traditionally recognized as spawning season), fishers do not fish, however, they continue hānai koʻa (feed fish at aggregation sites), which is believed to keep fish returning.

Fishers will chum with the palu or vegetable bait and knock on the boat to "call" the fish to the site. During catch season, as fish aggregate, feeding continues and a hoop-net is lowered (Image 2). Once fish are gathered, net is pulled up and fish brought into the boat. Since 2017, Hoʻokena ʻōpelu fishers have collected observational data on ocean currents and weather conditions as they relate to the seasonal fluctuations of ʻōpelu abundance and behavior at the koʻa, as a means to collect data that can set baselines specific to their place. Hoʻokena community seeks to better understand changes in ʻōpelu maturation, spawning times and water quality dynamics on the koʻa throughout the season and how that might impact the aggregation of ʻōpelu. Conservation International-Hawaiʻi has previously supported research on the reproductive assessment of ʻōpelu with fishers from Hoʻokena using validated methods for Hawaiʻi nearshore fishes (Schemmel *et al.*, 2016; Schemmel and Friedlander, 2017).

Research Objectives:

The overall goal of this project is to understand climate change impacts on the South Kona ʻōpelu fishery through integrated monitoring approaches resulting in a deepened understanding of critical fishery resources and that support the perpetuation of traditional ʻōpelu fishing practices.

This collaborative project aimed to empower communities as researchers and provide the necessary data to inform management action to ensure the ecological and economic resiliency and sustainability of the ʻōpelu fishery in South Kona. The research included four main components:

1. Monitoring of seasonal variability in ʻōpelu reproduction through monthly observations of ʻōpelu gonads, gonadosomatic index (GSI), histological assessment of reproductive state
2. Determining age of fish using otolith extraction and analysis to determine spawned date
3. Water quality monitoring on the koʻa during ʻōpelu harvest and hānai periods
4. A historical review of ʻōpelu fishery practices, seasonality, and climate trends through a literature review, historical catch records, and other documented sources.

In alignment with PI-CASC's Coastal Adaptation & Planning theme, this project supports Effective Community Adaptation Planning by providing key ecological data that helps coastal communities and government agencies develop innovative strategies to adapt to and mitigate climate change impacts on vital marine resources. This project supports the community's research questions and focused on four main outcomes:

1. Increased understanding of the coastal dynamics at ʻōpelu koʻa through combining environmental indicators, ʻōpelu reproduction information, and fisher knowledge.
2. Increased understanding of the spawning time of ʻōpelu through a reproductive assessment of South Kona ʻōpelu.
3. Increased understanding of the historical information of the ʻōpelu fisheries through research on seasonal and climatic changes.
4. Sustainable management and harvest practices are implemented within the South Kona ʻŌpelu Management Area based on traditional knowledge and accumulated scientific data.

This project involves multiple stakeholders working together to understand the status of the South Kona ʻōpelu fishery. By bringing together the diverse skills, perspectives, and expertise of collaborators, this project highlights the nexus between manager, practitioner, support organization, and research efforts that can support the long-term success of community- based conservation and collaborative management that is essential to the success of the state's Marine 30 X 30 initiative. This collaboration builds momentum to embrace and implement innovative and inclusive research efforts on climate change adaptation. This effort focuses on building community resilience through sustainable management of South Kona ʻōpelu stocks impacted by climate change. Furthermore, the knowledge gained from this research supports South Kona communities to reinforce and strengthen sustainable fisheries practices and support community and state management regulations in Hoʻokena. This project also facilitates long-term capacity for continued marine resource monitoring by providing scientific tools (water quality monitoring equipment), access to software and data analysis, and fisher training that will be sustained long after the project completion, as well as, handouts, presentations, posters etc. to use for community outreach and education.

Sample Collection

ʻŌpelu, *Decapterus macarellus,* gonad and otolith samples were donated and processed from the Hoʻokena, Hawaiʻi nearshore hoop net fishery. A total of 543 individuals (182 males, 304 females, and 64 individuals with gonads too small to be sexed) were collected between 12/5/2017 and 11/26/2019. Local Hoʻokena fishers caught and processed all the samples for this research with the support of Conservation International Hawaiʻi and the University of Hawaiʻi Hilo.

<u>Reproduction and Development</u>

Fish fork length (FL) was measured to the nearest 0.05 cm and fish weight and gonad weight was assessed to the nearest 0.01 grams. Entire gonad samples were preserved in buffered formalin for a minimum of three days. Gonad samples were rinsed overnight in fresh water and dehydrated through a series of ethanol dilutions (30%, 50%, 70%). Gonad samples were processed at the University of Hawaiʻi John Burns Medical School; embedded in paraffin, sectioned at 5 µm, and stained with hematoxylin and eosin counter staining. Reproductive state was diagnosed with modified criterial by Brown-Peterson *et al*., 2011 (Table 1; Figure 1 & Figure 2). When possible, resting females (regenerating) were differentiated from immature females by having two or more diagnostic criteria of prior spawning activity such as thick ovary wall, atretic oocytes, post ovulatory follicles, muscle bundles, and enlarged blood vesicles.

Analysis was done in R (Development Core Team R version 3.6.1 2019) using the statistical packages *boot, FSA,* and *lme4*). T-tests were done to determine if differences exist in fish size between males and females. Size at sexual maturity (L_{50}) was reported as the size at which 50% of individuals of a given sex are mature utilizing a logistic regression model with binomial family and logit link function (Chen and Paloheimo, 1994). Our reported L_{50} estimate only includes females collected during the spawning season. Due to difficulty differentiating undeveloped from regenerating females, all females with gonads with primary stage oocytes and no atresia were considered immature during the spawning season. Estimates for (L50) were generated through 1000 bootstrapped replicates of the model coefficients.

Age assessment

A subset of ʻōpelu were systematically selected and aged (n=47) by extracting sagittal otoliths (Image 3). All otoliths were arranged within sample dates by female or male and by size in mm. One otolith from each size class, for each sex, was chosen by the quality of the otolith after processing. Sex and size classes were not consistent across the full sample. To process, otoliths were embedded into a weigh plate of Bondo ® fiberglass resin and cured for no less than 24 hours. Once cured, plate was cut by 2 diamond wafering blades on an isometric low speed saw to create a 0.5 µm cross section. Each sample was separated and affixed to a slide using Crystalbond ™ 509-3 thermoplastic cement. Otoliths were polished using Buehler 400p800, 800p1500, 1200p2500 and Tex-Met C polishing cloths until daily growth increments were visible under a compound microscope. Images were taken via a camera mounted on the compound microscope at 160x magnification and daily growth increments were counted using ImageJ, scientific image analysis software. Otoliths rings were counted three separate times using a random order. Counts were averaged and those with >10% difference in range were recounted 2 additional times in random order. The mean of the two most similar counts were used in all otolith aging calculations, none being greater than 10% difference. A subset of otoliths processed (n=16) were further assessed to establish growth rate before capture by measuring 10-day growth ring increments from the centrum.

Water Quality

Water quality sampling was done by fishers on managed koʻa within the Hoʻokena fishing area with a Castaway ® CTD unit. Measurements were taken on 22 days between April 2019 and November 2019. To collect a "cast", unit was allowed to drop freely (max depth of 14.08 m) and slowly pulled back up to the surface. Temperature (°C) and salinity (PSS-78) measurements from the "up" recording was used. Excel was used to display mean water temperature and salinity throughout the water column per month.

Commercial Catch Data

Hawaiʻi Division of Aquatic Resources 1948- 2019 ʻōpelu commercial catch data for the west side of Hawaiʻi Island was used for analysis (HDAR, 2019). All analyses were completed in Excel. Commercial catch in Hawaiʻi is reported by zones of inshore areas, described as high-water mark to 2 nautical miles offshore, and complementary offshore zones, described as area 2 nautical miles offshore to approximately 20 nautical miles offshore (Image 4). Zone 100 inshore area has a corresponding offshore zone of 120, zone 101 inshore zone corresponds with offshore zone of 121 and so forth. All commercial catch data in this report represents publicly available data sets. Due to confidentiality issues, any month in which there are 3 or few fishers for a fishing method or zone, data are removed to protect fisher's privacy. Hoʻokena is in zone 101 which starts a Keāhole point and continues south to Hoʻopuloa (1 mile north of Miloliʻi), which is also the most active zone for ʻōpelu fishing (HDAR 2019, McNaughton, 2008).

Results

Reproduction and Development:

A total of 161 males and 267 females Decapterus macarellus were assessed for reproduction. Females ranged in size from 17.0 cm to 29 cm fork length (mean 21.9 cm) and males ranged in size from 18.5 cm to 27 cm fork length (mean 21.9 cm) (Figure 3). There was no difference between female and male mean size (t=-0.23, df=381.99, p-value=0.82).

We found a unimodal oocyte size distribution, suggesting group synchronous oocyte development (i.e. a single cohort of oocytes to be spawned during the next spawning event). It is unclear how fast oocyte maturation is in this species and if an individual female is capable of multiple spawning events during a spawning season.

Female gonadosomatic index values peaked April through August (Figure 4). Spawning capable females were observed in March through August, with a peak from March through June (Figure 5 A & B). Some spawning capable females were observed with post ovulatory follicles and other evidence of recent prior spawning (Figure 2 F). Females may be capable of spawning multiple batches during the spawning season. There were a few females with post ovulatory follicles and late stage vitellogenic oocytes suggesting that spawning was recent and that another spawning may take place in the near future (Figure 2 F). From the pattern in oocyte development, it appears that the latest stage of oocytes are all recruited and mature as one cohort but are spawned over multiple days. Or alternatively, partial spawning could take place and the remaining mature oocytes may be retained within the ovary and reabsorbed.

We did find multiple lines of evidence that some spawning may be occurring outside the spawning season. A few females with regressed ovaries were found in October, November and December, with gonads that had atresic vitellogenic oocytes and healthy primary oocytes (Figure 2 C & D). A few females with developing gonads were observed in November and December (Figure 5 A & B).

It was very difficult to differentiate the gonads of immature females (undeveloped) from those of regenerating (resting, mature) females (Figure 1). For many of the females with inactive gonads (only primary stage oocytes), the gonad phase identification between undeveloped (immature) and regenerating (resting, mature) was inconclusive (Figure 1 E & F). For many of these individuals, there was not two or more lines of evidence of prior spawning (thick gonad wall, atresia, muscle bundles, large blood vessels), however the gonad was disorganized and had large interlamellae spaces that is often associated with regenerating females.

Female size at maturity was assessed from females during the spawning season (March-August). All undeveloped females and regenerating females with gonads with primary stage oocytes and no atresia (Table 1) were considered immature during the spawning season. Female size at maturity (L_{50}) was found to be 21.8 cm (CI = 21.6 cm, 22.5 cm) (Figure 6). For the Hoʻokena hoop net fishery, 72% of females sampled were found to have undeveloped gonads. Due to the uncertainty in differentiating immature from regenerating females, we do not know what percentage of the females are immature in this fishery. Male size at maturity (L_{50}) was inconclusive given the sample size and variability in male size at maturity.

Age assessment

Otoliths from a total of 47 ʻōpelu were prepared and used for age estimation. Mean (±SE) fork length of ʻōpelu subset used for age estimation was 226 ± 2 mm (22.6 ± 0.2 cm) FL and ranged between 198 – 270 mm (19.8-27.0 cm) FL. The mean (±SE) age at capture of the subsample of ʻōpelu used for age estimation was 80 ± 3 days old, but individuals between 39 – 139 days old were captured. There was no difference in mean FL between the sexes ($F_{1,44} = 0.02$, $P = 0.88$) and no relationship between FL and age was observed ($F_{1,44} = 0.10$, $P = 0.76$; Figure 7). While this is an unusual finding, it was not unexpected given the narrow range of FL of the ʻōpelu examined (Figure 7). There was no difference in the mean age of ʻōpelu examined from the six samples taken between December 2018 –May 2019 ($F_{5,41} = 0.62$, $P = 0.68$; Figure 8). ʻŌpelu seem to grow very rapidly, averaging approximately 2.2 ± 0.1 mm d^{-1} ($F_{1,114} = 1210.08$, $P < 0.01$), although some individuals seem to be capable of maintaining considerably higher growth rates (Figure 9). The Von Bertalanffy growth function fitted to the mean back-calculated length-at-age data yielded parameter estimates (±SE) for L_∞, k, and t_0 of 250.30 ± 5.55 mm (25.0 ± 0.5 cm) FL, 8.02 ± 0.54 $yr.^{-1}$, and 0.001 ± 0.003 yr., respectively. However, growth of the individuals examined seemed to slow considerably at approximately 200 – 220 mm (20.0-22.0 cm) FL or 70 – 90 days (Figure 8).

While hatch dates of ʻōpelu were observed throughout September 2018 – March 2019, there were distinct concentrations during late October through mid-December and February through March (Figure 10). While this is suggestive of multiple spawning pulses per year, the sample size was too small to eliminate the possibility that ʻōpelu spawn continuously throughout the year. Regardless of the time of year they occurred in, hatch dates tend to be more frequent between the last quarter and first quarter of the moon relative to the period between the first quarter and last quarter (Figure 11). This distribution of hatch dates suggests that ʻōpelu spawning may be more likely to occur in association with darker nights near the new moon as opposed to brighter nights near the full moon.

Gonadal-somatic index was not related to the age of an individual, even when sex and FL was accounted for ($F_{3,44} = 2.02$, $P = 0.13$; Figure 12). Small sample size is likely to blame for lack of relation.

Water Quality

Water quality measurements were taken on 22 days between April 2019 and November 2019 with a total of 101 usable "casts". Mean water temperature over all depths (surface-14.08m) varied per month, lowest mean temp (26.1°C) in April and highest in October (28.2°C) with temperature consistently rising through October and dropping slightly in November (Figure 13). When temperatures at each depth were analyzed, we found that there was a greater variability through the water column during summer months (May- August) when sea surface temperatures rise, and more stable throughout the water column in spring and fall months (April, October-November), when SSTs are more consistent with temperatures at lower depths (Figure

14). All standard errors were calculated to be no greater than 0.08 so they were not reported.

Mean salinity was measured in Practical Salinity Scale-78, formulated and adopted by the UNESCO/ICES/SCOR/IAPSO Joint Panel on Oceanographic tables and Standards, Sidney, BC, Canada, 1-5 September 1980. Salinity throughout all depths ranged from 31.77 to 34.64 (Figure 13). Mean salinity for combined depths rose consistently from April (mean salinity 34.03) through June (mean salinity 34.37) then dropped in July to 34.31 mean salinity and gradually rose through November (mean salinity 34.58) (Figure 15). Range for mean salinity throughout the water column 34.03-34.58. All standard errors were calculated to be no greater than 0.04 so they were not reported.

Commercial Catch

Hawaiʻi ʻōpelu commercial catch reported for 2018 was 118,603 lbs. for all catch methods, all reporting zones. In the South Kona region, zone 101 (Keāhole point to Hoʻopuloa) (Image 3) reported 64,757 lbs. (all methods) which accounts for more than 52% of the states reported catch. If the corresponding offshore zone of 121 is included that number jumps to 71,161 lbs. (just over 60%) of the state's total catch. No other zones in west Hawaiʻi reported commercial catch of ʻōpelu in 2018, or more likely, too few of fishers reported for data to be public record.

For west Hawaiʻi Island, ʻōpelu fishers using all methods, reporting from 1948 – 2018 reported a total catch of 8,671,805 lbs. Of that catch, zone 101 comprises ~75% of the catch. Making it the most important commercial ʻōpelu fishery on Hawaiʻi Island (Figure 16). If methods are separated, hoop-net catch 1948-2018 was reported as 3,438,782 lbs., handline catch = 2,922,815 lbs. and other methods = 151,920 lbs. (Figure 17).

While many South Kona ʻōpelu fishers have reported declines in recent years, the ʻōpelu fishery appears to have a boom and bust cycle, similar to other fish of its size (anchovies, sardines etc.) (Figure 18). Catch Per Unit Effort (CPUE) was not calculated for this study so causation could be from increases/ decreases in effort or from population changes in fishery.

Hawaiian Oral History of ʻŌpelu in South Kona

Oral history interviews conducted by Kepa Maly (2002) with kupuna from South Kona uncover information about the ʻōpelu fishery, it's importance, Hawaiian terminology and practices associated with it. Louis Hao talks about hānai ʻōpelu starting 2-3 months before the ʻōpelu come in February and continue through the season. They would only use maunu (bait) consisting of kalo pakē (Chinese taro) and pumpkin to hānai ʻōpelu. The ʻau kai (currents) were very important to him and other fishers, if you follow the currents, it will take you to the koʻa. Once the currents change you would adjust your position on the koʻa. He has seen changes in fishing attitude from the past and talks about how nobody respects the fisher and their fishing area like before.

Walter Paulo, a kupuna from Nāpoʻopoʻo also describes his experiences growing up ʻōpelu fishing and how the currents were very important for their fishing practices. He notes how the ʻōpelu fishery is seasonal and generally starts in May and they would hold ceremony to observe "a manawa lawaiʻa" the start of the fishing time. He also mentions that in 1925 a bill was introduced to kapu (ban) the use of ground up aku or ʻahi in their palu (chum) because it attracted pōwā (predators). He also mentions, because they didn't use ice, the bacteria generally deteriorate fast in the stomach with this type of fish bait. The law under the territory of Hawaiʻi was amended in 1950 so people could start to use the fish bait again, except from Kaunā to Kiʻilae (ahupuaʻa in South Kona), which the fish bait is still illegal till today.

In 1976, Smith Kaleohano was interviewed by Larry Kimura and identified many of the same traditions explained in the Maly interviews including the use of vegetable bait, kapu seasons and ceromonies to start the ʻōpelu catch season. He also explained that kapu seasone was set by the poʻo lawaiʻa (head fisherman) who was chosen local fishermen as the fisher with the best luck and vast knowledge. The poʻo lawaiʻa would carefully observe the fishery and when the fish became large enough, the kapu was lifted and those from the area could fish for ʻōpelu and likewise, close the season as the fish began to shift into spawning season. If someone was caught with an ʻōpelu net on the canoe when there was a kapu, the net would be confiscated and burned. During the kapu each fishing family would take weekly turns to go out and hānai ʻōpelu koʻa, with the exception of winter when there was rough water.

Discussion

The nearshore, hoop-net fishery in Hoʻokena is composed of young ʻōpelu, ranging in age from 39 to 139 days old with an average age of 80 ± 3 days. From samples collected from 2017 to 2019, we found a pronounced spawning season from March to August. Female size at maturity (L_{50}) was found to be 21.8 cm, smaller than prior *Decapterus macarellus* estimates of maturity from Hawaiʻi (Clarke and Privitera, 1995; McNaughton, 2008; Yamaguchi, 1953).

Spawning peaked during summer months from April through June. This is consistent with previous research (Clarke and Privitera, 1995; McNaughton, 2008; Yamaguchi, 1953). However, we found evidence that a small proportion of ʻōpelu from the nearshore fishery spawning outside of the spawning season. Estimated ages suggest that spawning is occurring throughout the year, which aligns with McNaughton's 2008 study. We found nine regressed females and five developing females outside of the spawning season. However, we did not observe any spawning capable or actively spawning females outside of the spawning season. For this research, we only sampled the nearshore, hoop-net fishery. Larger individuals are caught in the hand-line fishery offshore and may have extended spawning seasons compared to the individual's nearshore fishery and may be contributing to recruitment in the Hoʻokena nearshore fishery.

Unfortunately, we were not able to determine spawning frequency. However, oocyte developmental patterns can help inform spawning frequency. We found a unimodal oocyte size distribution for *D. macarellus*, which may be single cohort of oocytes to be spawned during the spawning season or an artifact of a long spawning frequency interval over the course of a protracted spawning season. It is unclear how fast oocyte maturation is in this species and if an individual female is capable of multiple spawning events during a spawning season. However, our pattern of oocyte development needs to be confirmed for mature females sampled at dusk and nighttime since McBride *et al*., (2002) found a unimodal oocyte size distribution for female *D. punctatus* sampled during the diel cycle (daylight) and a bimodal oocyte size distribution from *D. punctatus* females sampled at dusk. Whaylen *et al.,* (2004) found *D. macarellus* in Cayman Islands to spawn within a week of the full moon and between 1 and 8 minutes after sunset during the last week of January and the first week of February. The study did not do morning monitoring, so it is unclear from their results if diel spawning was occurring as well. McNaughton's 2008 study suggested that spawning at dawn in or around the net fishery is likely however, his study, found no spawning individuals.

This study found a smaller size at maturity (21.8 cm fork length) compared to McNaughton (2008) (25.7 cm standard length, ~26.8 fork length), which is likely a result of the methods used to assess maturity. Clarke and Privatera (1995) estimated first size at maturity at 24.5 cm standard length (~25.5 cm fork length).

Our estimate of size at maturity (L_{50}) was constrained to the spawning season. This is a common practice for reproductive assessments as it can increase accuracy in the estimate. We did this because it was difficult to differentiate immature undeveloped females from regenerating females. During this time there should be fewer regenerating females and therefore we assumed that the undeveloped female gonads were immature. Constraining L_{50} estimation during the spawning season should result in larger estimates of L_{50} than if assessed using females sampled across the entire year.

We observed fast growth and early maturity, with spawning females as young as 61 days old and a mean of 76 days old. Length at maturity was found to be variable, likely due to fast growth of this species and possibly individual variability in growth. This may be caused by water temperature and food availability during hatching and juvenile growth. Additional otolith collection and processing could produce a better understanding of how fast ʻōpelu grow within the hoop-net fishery.

Sea surface temperature plays a vital role in many marine ecological processes. The water temperature data collected for this study were not enough to make any overarching assumptions. However, it has created baseline data for water temperature in a remote area of Hawaiʻi that has a fairly narrow range, likely making it very susceptible to impacts from small shifts. Fishers have been trained to collect water quality data using the Castaway ® CTD unit and will continue to collect data around the nearshore ʻōpelu fishery. We found, as expected, sea surface temperatures rise in the summer months which causes a larger gradient of temperatures within the water column, though there are only small differences. Global sea surface temperatures are rising and if the warm waters of South Kona continue follow this trend, ʻōpelu may move out to deeper waters where it is cooler. This would create an additional challenge for hoop-net fishers and potentially ending this fishery that is so important for food security and cultural traditions. Biological function as intermediary predator/prey will also be affected if ʻōpelu move offshore, possibly contributing to trophic shifts in other economically important fisheries.

Osmoregulation of sea water is an essential function of life for a marine fish. Fishes that live in narrow ranges of salinity, like the Kona coast of Hawaiʻi are called stenohaline and have a narrow tolerance of changes in salinity. Data collected with the Castaway ® CTD unit confirmed that there is a narrow range throughout the water column over summer months. The salinity data set was also too small to make large statements but has created a baseline and an ongoing log of conditions that may be used to inform future conservation action in the South Kona district of Hawaiʻi Island.

Commercial catch and oral histories portray a rich and robust connection between the people of South Kona and ʻōpelu. Its trophic position means it is also an important component in many other fisheries of pelagic, economically important fishes. Though the fishery is not believed to be in danger of depleted levels, it is important to assure the health of the fishery for generations to come.

Impacts on Management and Future Partnerships

The benefits of the project have been realized by the community and project participants and the outlook for expanded collaborative and community-driven research in the future are positive. The West Hawaiʻi coast and it's culturally and economically valuable fisheries continue to be a high priority for collaborative co-management. As environmental changes and their impacts continue to be better understood, communities, with DLNR-DAR support, can co-develop appropriate response and mitigative actions to ensure the health and productivity of critical marine resources and the human populations that depend on them. As discussed above, this project provides specific baseline detail into the reproductive timing of ʻōpelu, information that plays a key role in decision-making related to appropriate harvest periods, limits, and jurisdiction (i.e. changes in traditional aggregation site locations). Additionally, the documentation of baseline ocean temperature and salinity ranges is key for discussing potential impacts due to continued environmental and climate change. Information from this project will be made available to DLNR-DAR biologists and liaisons to support continued collaborative management discussions on community-specific as well as regional management actions that ensure the vitality of the West Hawaiʻi ʻōpelu fishery.

To ensure the best management recommendations can be made, the authors suggest further gonad and otolith data collection to increase the sample size and collection periods to better understand potential shifts in spawning (i.e. size at maturity) and season. Due to the migratory nature of ʻōpelu, the authors also recommend similar ʻōpelu data collection in other communities to expand the geographic range of the effort therefore allowing for an examination into potential regional impacts and shifts in fish biology and behavior.

This project serves as an effective and culturally appropriate model for community-based climate change adaptation and resilience research applicable to numerous community-driven efforts across the state in various co-managed areas. The project process included the development of a community-driven collaborative document detailing the purpose and focus of the project as well as specifically outlining key parameters of the partnership. In the last decade, research partnerships have increasingly grown to include key stakeholders and communities who typically provide key information and significant contributions to research outcomes.

Unfortunately, individuals and communities, specifically indigenous communities, have often been left vulnerable and unrepresented in these partnerships, and in extreme cases have resulted in the loss of intellectual property rights and ownership of traditional and indigenous knowledge traditionally held as communal assets. As a result, this project prioritized the development of a memorandum of understanding (MOU) that specifically identified intellectual property rights and sensitive information protections and addressed ownership and appropriate use of indigenous knowledge shared, described, or developed during the course of the project. Additionally, the MOU details the commitments towards respectful engagement and a focus on long-term collective benefits versus an outcome with singular party benefit.

The development of the MOU has large implications for supporting community-driven collaborative work in numerous research settings. Having been done by and between two community organizations and the University of Hawaiʻi, this MOU may serve as a model for future state entity and community partnerships. Alongside other similar works that look to recognize and equalize the contributions indigenous individuals and communities make to research and management in Hawaiʻi, the development of this MOU takes the necessary steps to address historical missteps and contribute to a new paradigm of equity and respect in collaborative research efforts.

In order to broaden the reach of this project, the research results, process, and descriptions of products will be shared with interested communities and individuals as deemed appropriate by Hoʻokena and Miloliʻi communities. Outreach efforts may include school outreach and other education activities, presentations given in community-based conservation network gatherings including Kai Kuleana, E Alu Pū, and Alahula ʻĀina Momona. All members of the collaborative team will contribute to the development and implementation of post-project research outreach activities in South Kona and across the state. Posters and handouts created for KUPA Friends of Hoʻokena Beach Park were created to help share the work done through this project and will be updated with work done in the future (Images 4, 5, and 6).

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Image 1: Hawai‘i Island; Insert of Ho‘okena ‘ōpelu project area including ahupua‘a deliniations. Maps derived from Office of Hawaiian Affairs Kipuka website: http://kipukadatabase.com/kipuka/

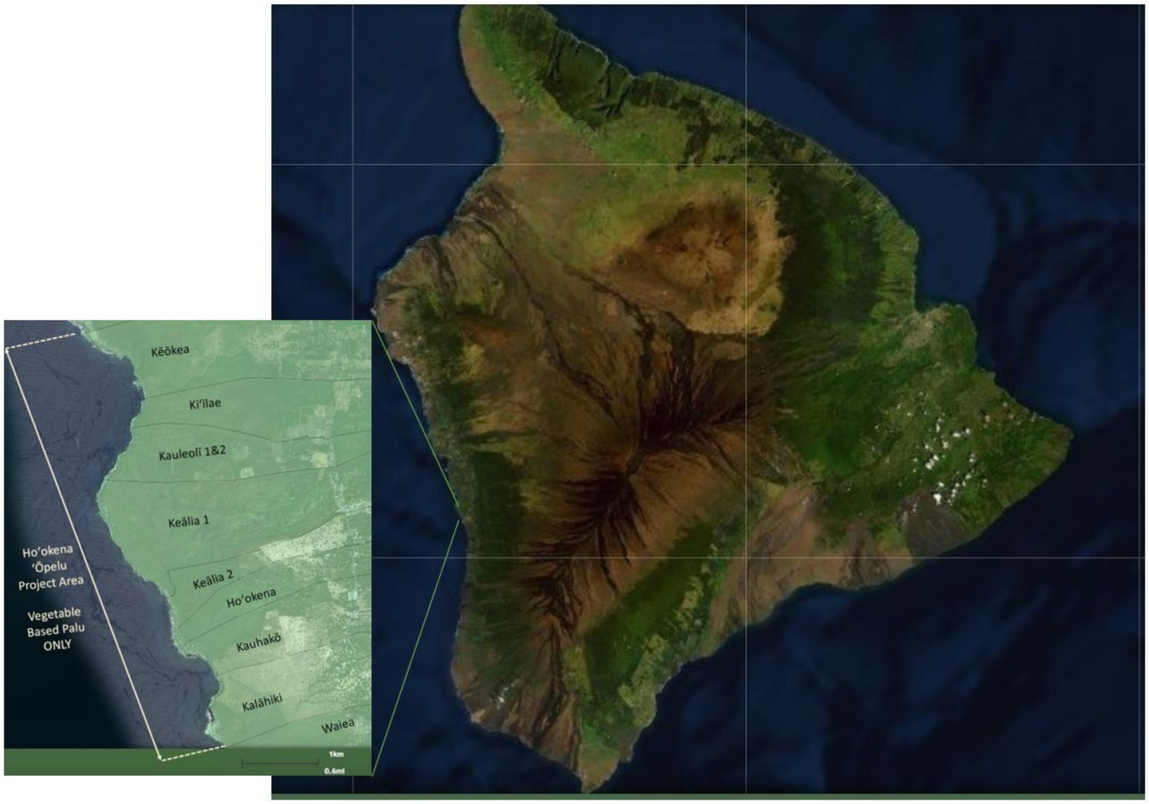


Table 1. Reproductive state classification schema for female *Decapterus macarellus.*

Reproductive State	Mature	Diagnostics
Undeveloped	No	Ovaries with oogonia and primary growth (PG) oocytes (chromatin-nucleolus and perinucleolar) present. Thin ovary wall.
Developing	Yes	Cortical alveolar oocytes, and/or early vitellogenic oocytes, VTI and/or VTII, present.
Spawning Capable	Yes	Presence of late stage vitellogenic oocytes (VT IIII), identified by dramatic increases in oocyte size and uniform distribution of yolk. May contain hydrated oocytes and postovulatory follicles (POFs).
Regressing	Yes	The ovary wall is thick, does not contain healthy vitellogenic oocytes, and the ovary may contain unabsorbed material from past spawning events (atretic oocytes and POFs).
Regenerating	Yes	Only primary growth oocytes are present. The ovary wall is thick, and the ovary may contain unabsorbed material from past spawning events.

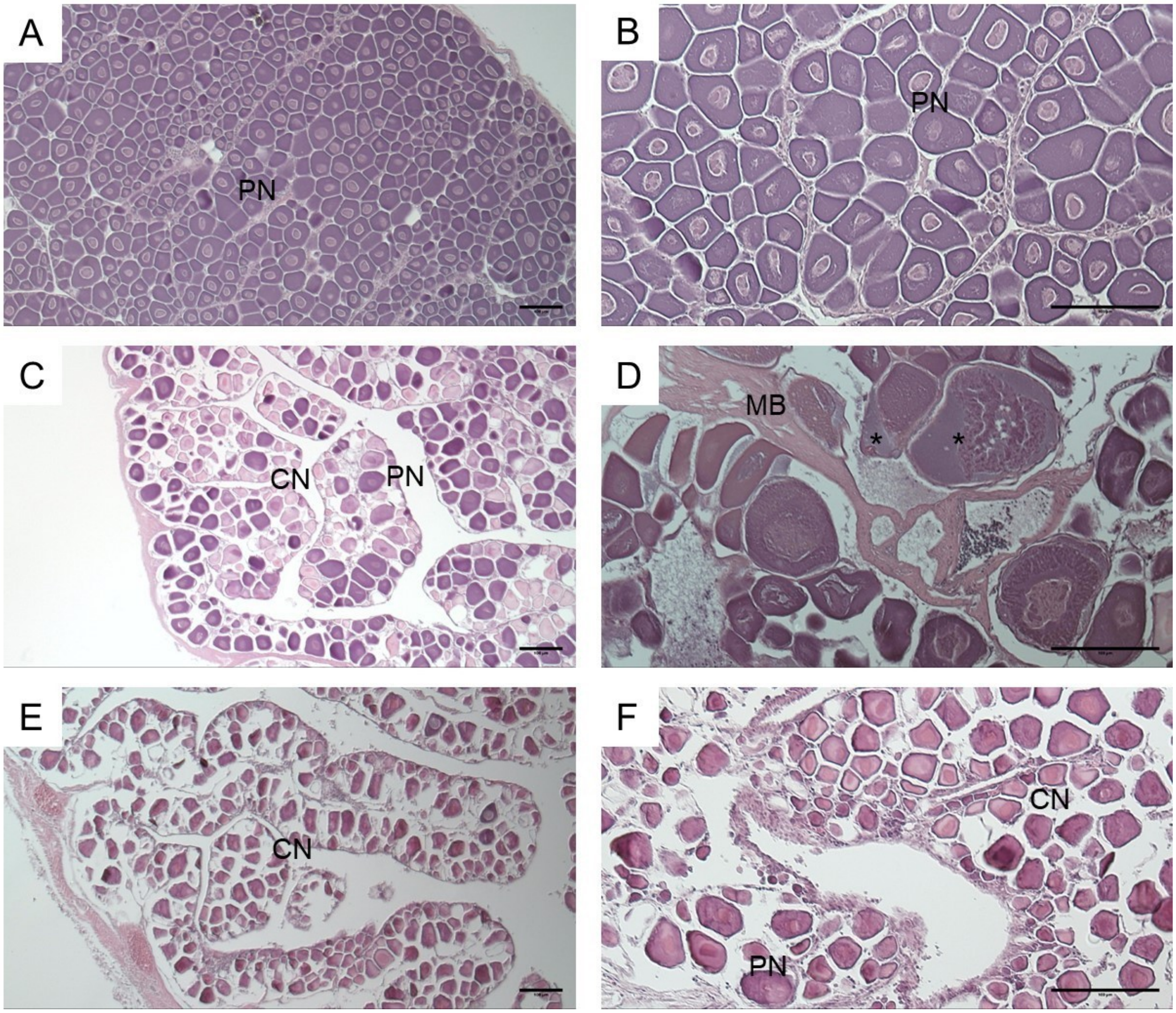


Figure 1. Female ʻōpelu, *Decapterus macarellus,* what we think is an undeveloped individual however cytoplasmic oil droplets are present which can occur more frequently in regenerating individuals (A &B), regenerating individual with muscle bundles and aretic oocytes (C & D), and individual with an unknown reproductive phase that is either an undeveloped or regenerating (E & F) (PN= perinucleolar; chromatin nucleolar; MB = muscle bundle). All scale bars are 100 µm.

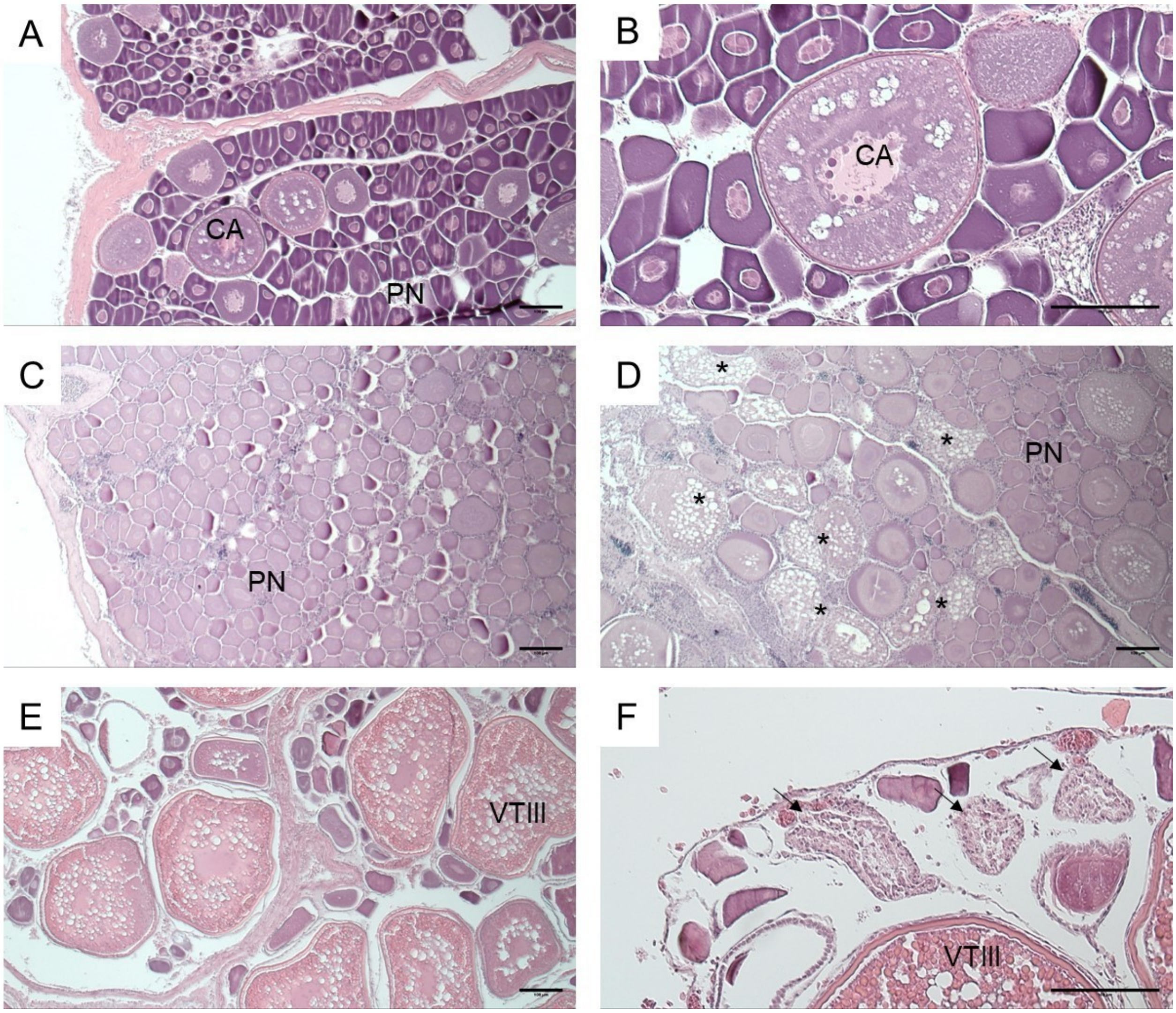


Figure 2. Female ʻōpelu, *Decapterus macarellus,* developing (A &B), regressing (C & D) and spawning capable (E & F) reproductive phases (PN= perinucleolar; CA= cortical alveolar; * = atretic oocyte; VTIII= vitellogenic III; arrows indicate post ovulatory follicles). All scale bars are 100 µm.

Image 2. Image of traditional Hawaiian style ʻōpelu fishing by Eric Enos (in Paulo *et al.*, 2015)

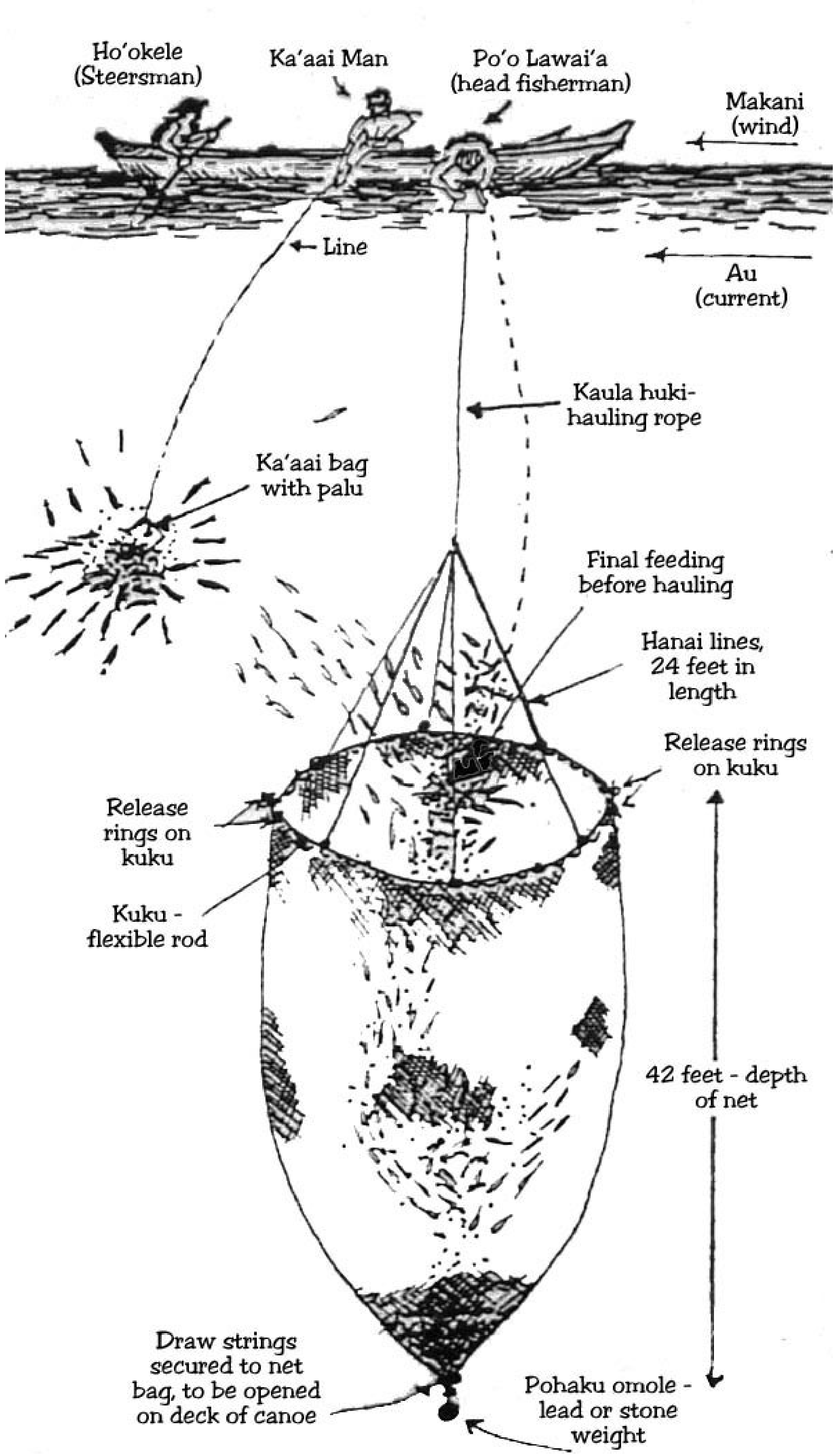
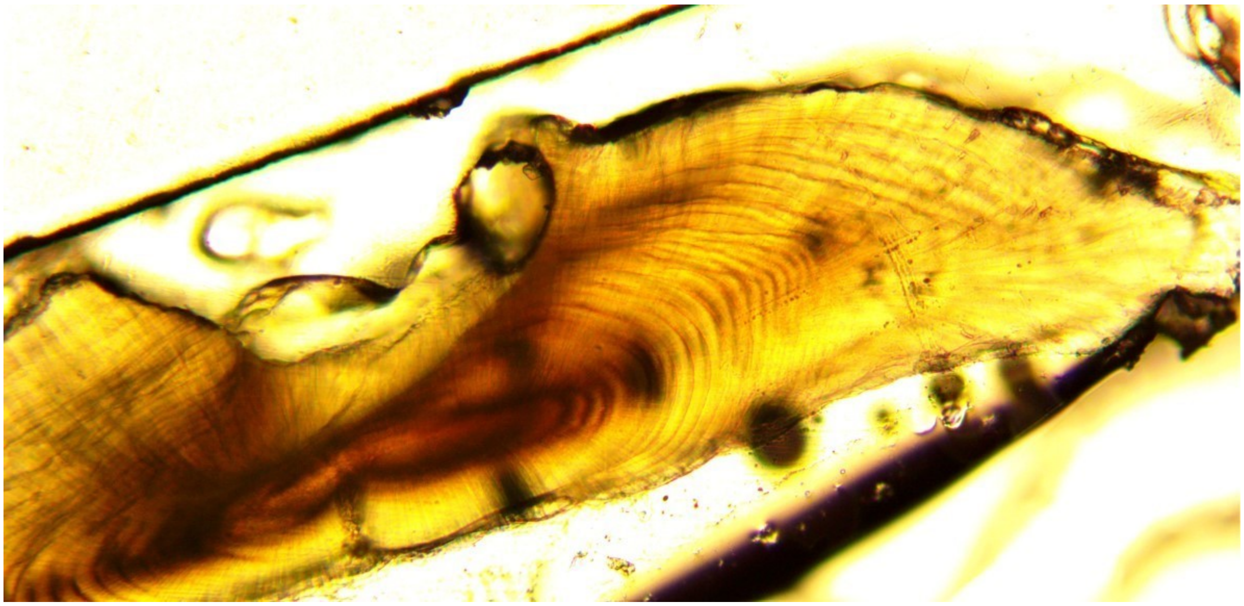


Image 3. Sagittal otolith used in aging calculations



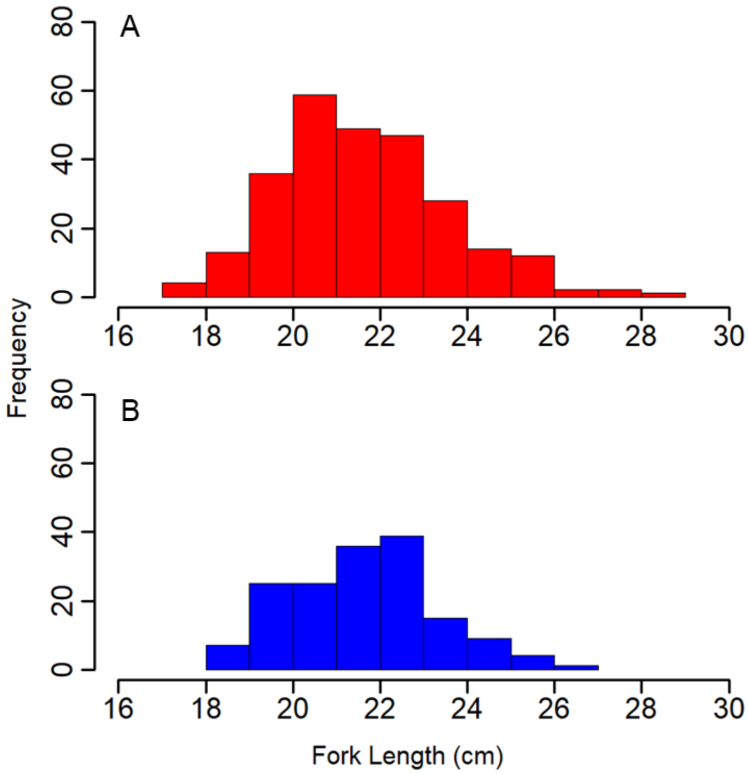


Figure 3. Size frequency distribution of *Decapterus macarellus* females (red) and males (blue) sampled from the Ho'okena hoop line fishery.

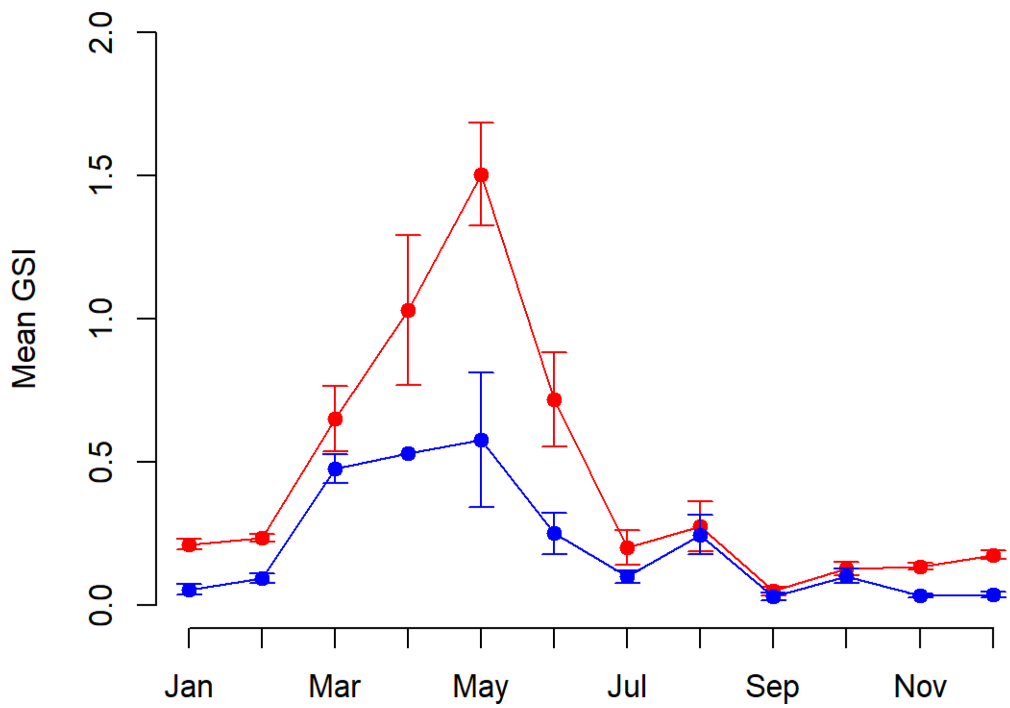
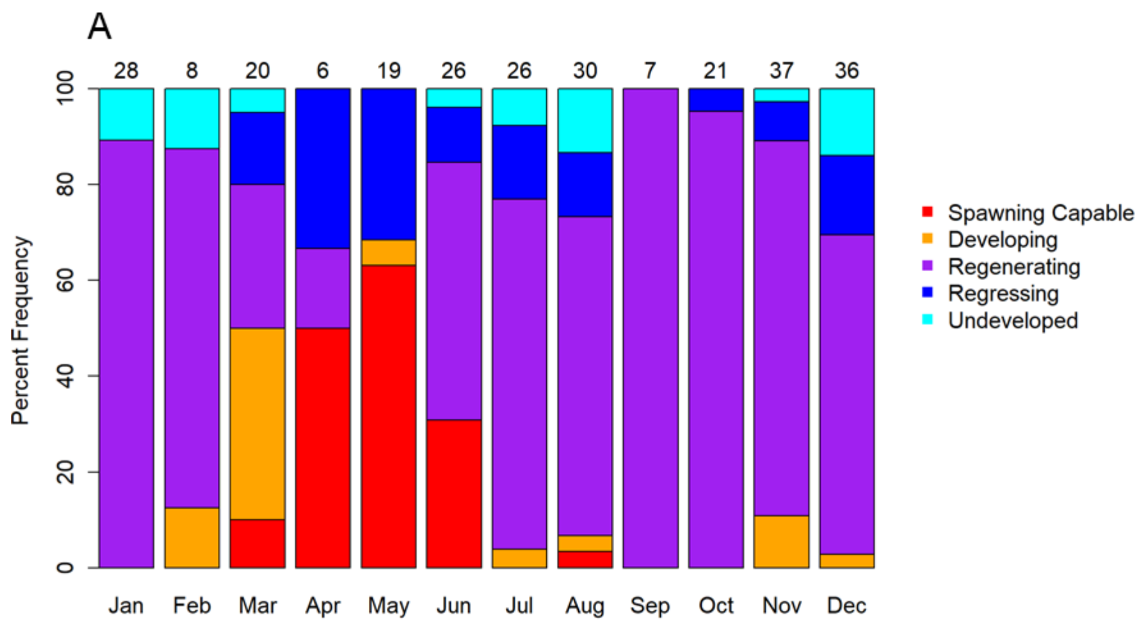


Figure 4. ‘Ōpelu, *Decapterus macarellus*, mean monthly gonadosomatic index (GSI) for females (red) and males (blue). Error bars represent standard error.



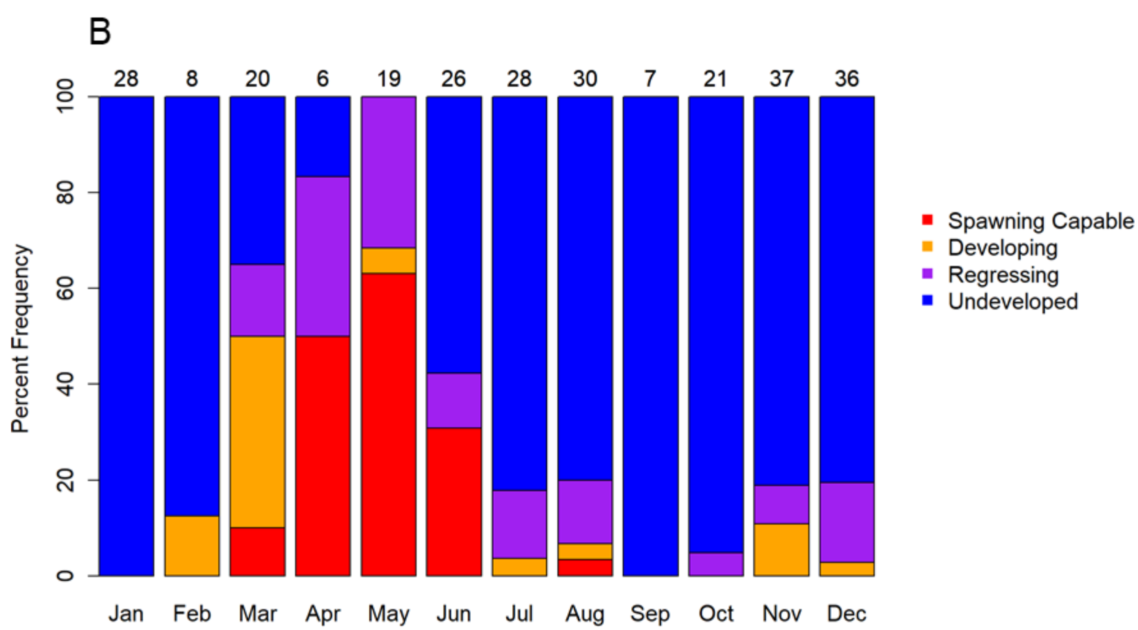


Figure 5. Month proportion of female *Decapterus macarellus* reproductive phases. (A) Regenerating and undeveloped females were differentiated as best as possible using standardized criteria described in Brown-Peterson 2011. (B) All undeveloped and regenerating females were lumped into the undeveloped phase due to uncertainty in differentiating immature from regenerating female gonads.

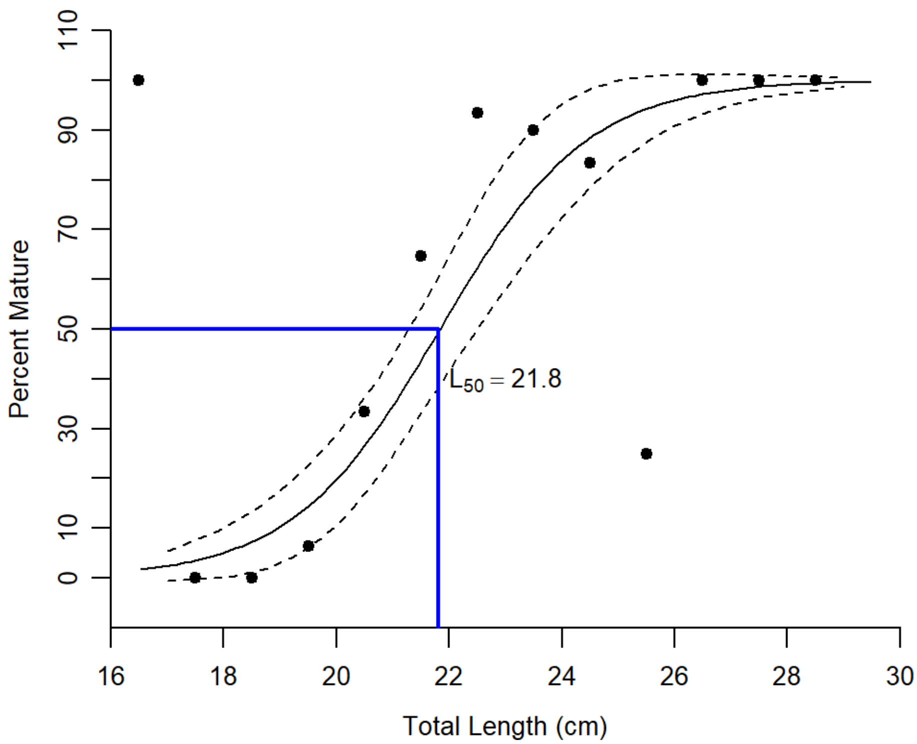


Figure 6. Female ʻōpelu, *Decapterus macarellus,* size at maturity (L50) from the hoop net fishery in Hoʻokena

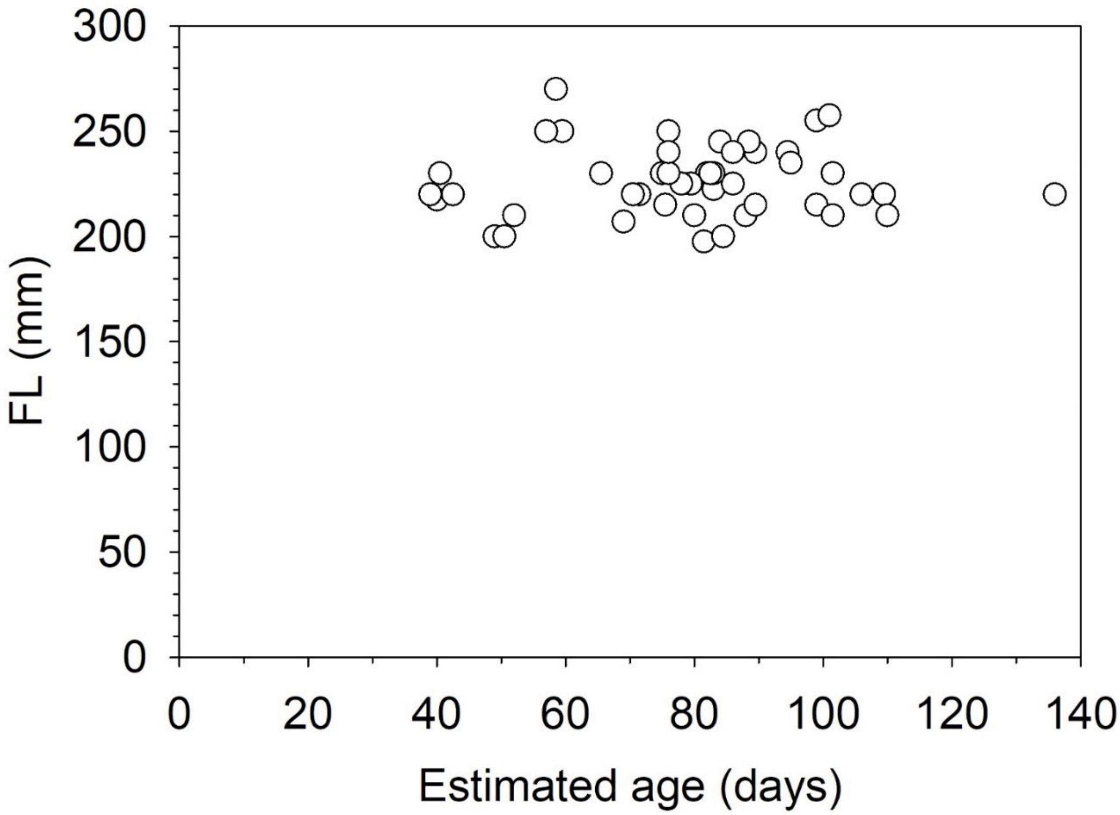


Figure 7. Relationship between fork length (FL) and age of ‘ōpelu, *Decapterus macarellus* (n = 47) captured from Ho‘okena on the west side of Hawai'i Island, Hawai'i, during December 2018 – May 2019. Age was estimated by counting daily increments on the sagittal otoliths.

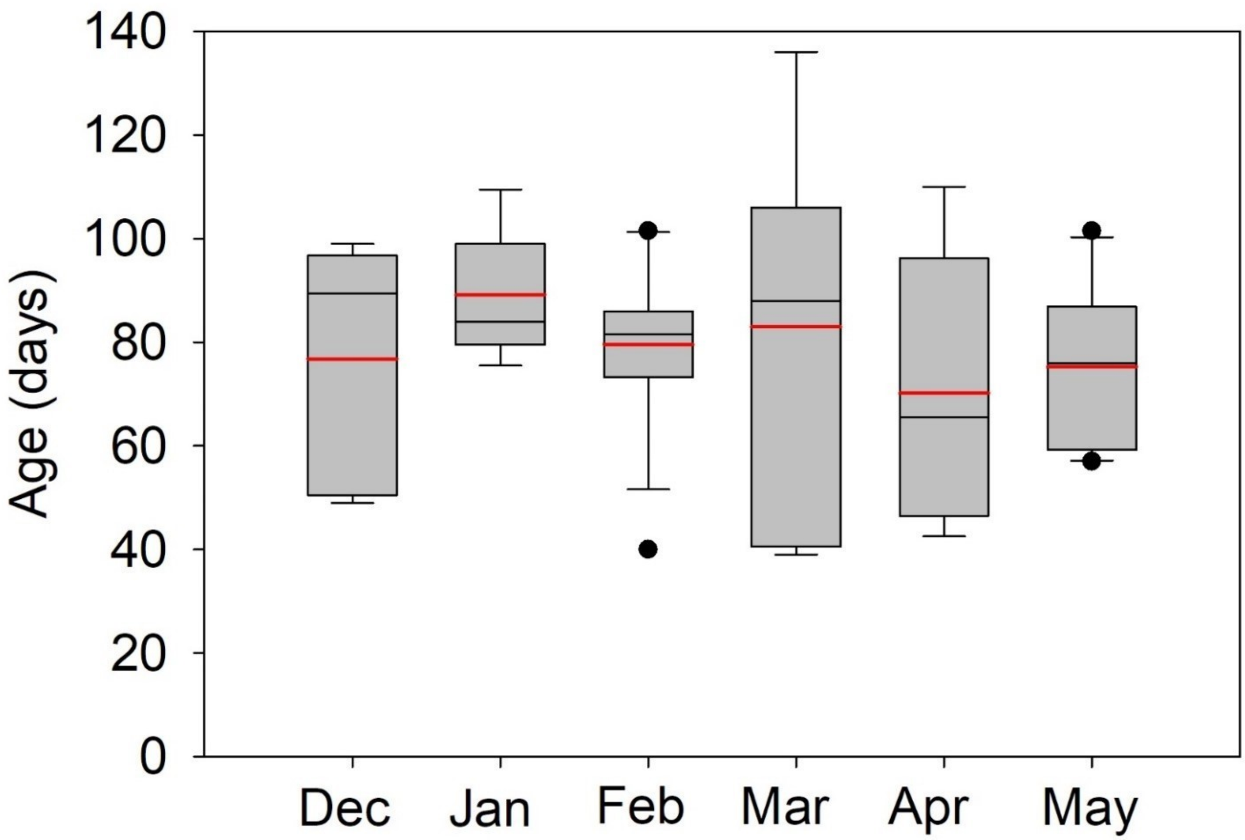


Figure 8. Boxplot of the age distribution of ʻōpelu, *Decapterus macarellus* (*n* = 47) captured from Hoʻokena on the west side of Hawai'i Island, Hawai'i, during December 2018 – July 2019. Red lines indicate the mean age.

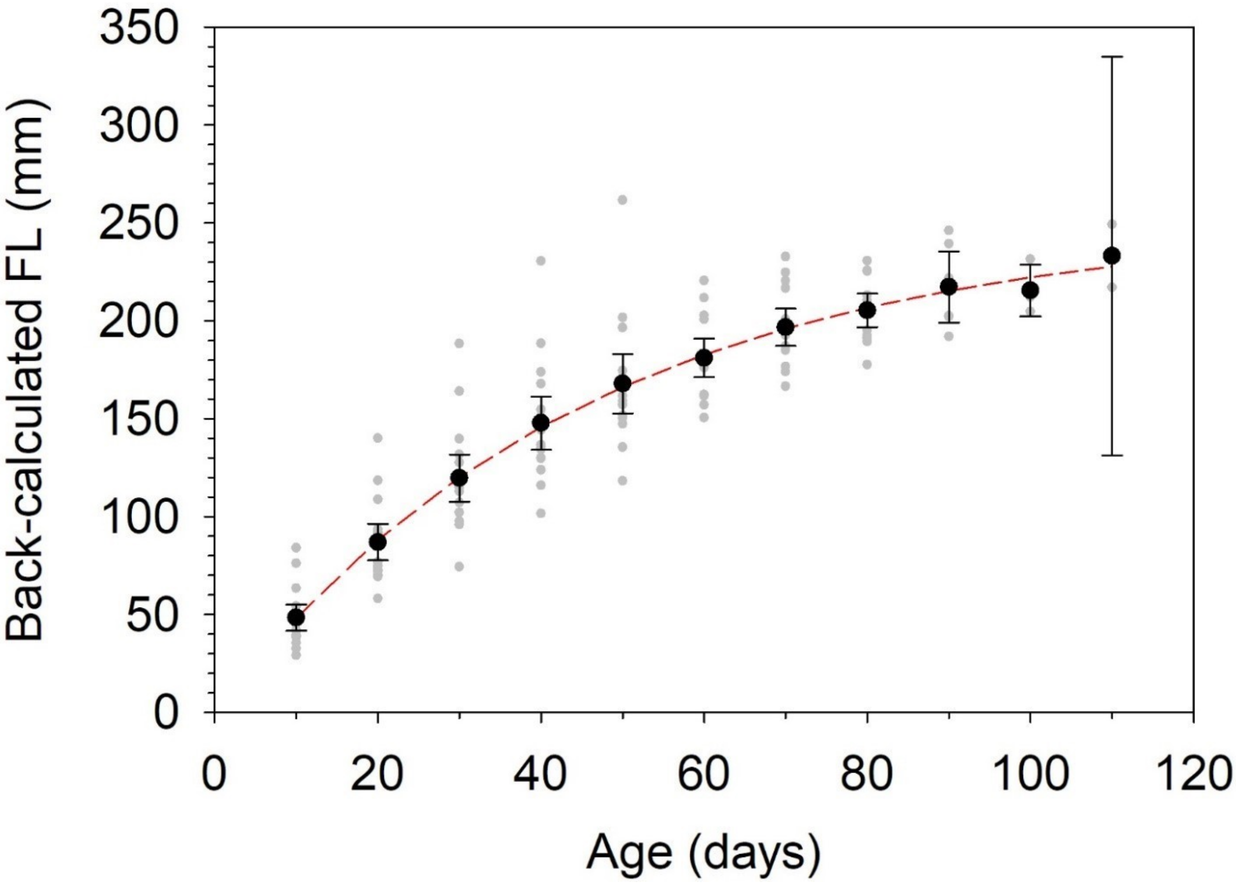


Figure 9. Relationship between back-calculated fork length (FL) and age of ‘ōpelu *Decapterus macarellus* (n = 47) captured from Ho‘okena on the west side of Hawai'i Island, Hawai'i, during December 2018 – May 2019. Observed back-calculated lengths-at-age are represented by gray circles while the mean back-calculated lengths-at-age are represented by black circles with error bars showing 95% confidence intervals. The red dashed line represents the values of FL at age predicted by a Von Bertalanffy growth function fitted to the mean length-at-age data (L_∞ = 250.3 mm FL, k = 8.0 yr^{-1}, and t_0 = 0.001 yr.).

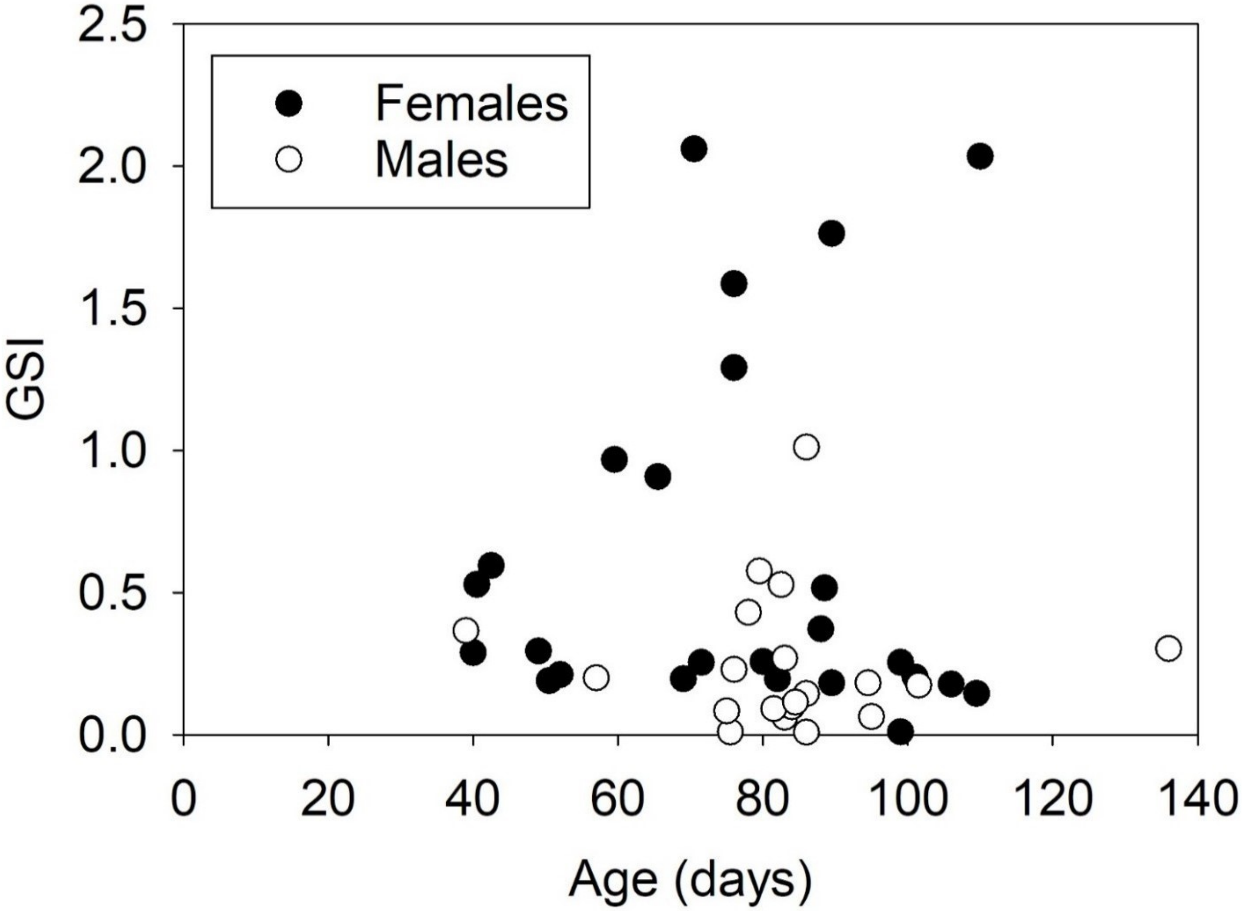


Figure 12. Relationship between age and gonadal-somatic index (GSI) of ‘ōpelu, *Decapterus macarellus* (*n* = 47) captured from Ho‘okena on the west side of Hawai'i Island, Hawai'i, during December 2018 – May 2019.

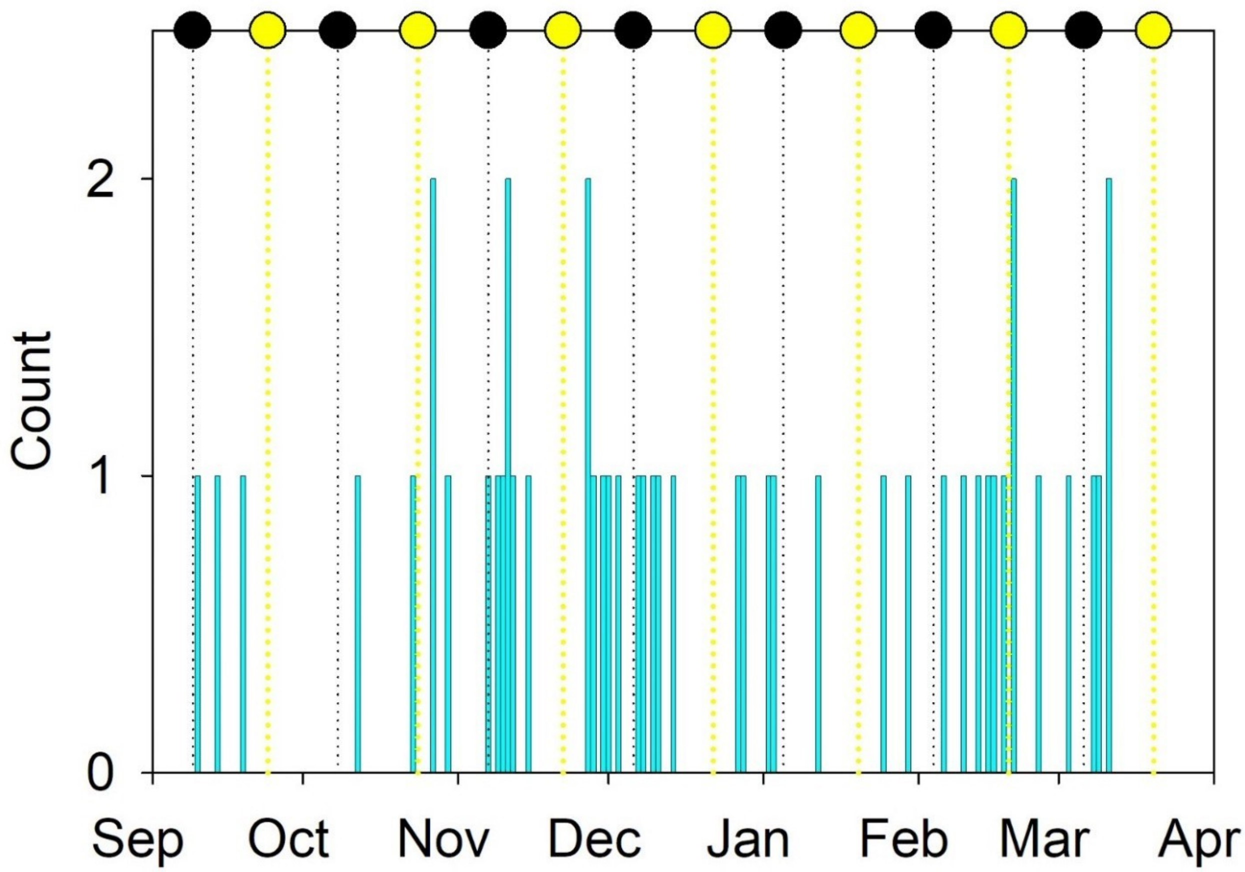


Figure 10. Distribution of hatch dates (September 2018 – March 2019) of ʻōpelu *Decapterus macarellus* (*n* = 47) captured from Hoʻokena on the west side of Hawai'i Island, Hawai'i, during December 2018 – May 2019. Black circles and associated dotted lines indicate new moons, while yellow circles and associated dotted lines indicate full moons.

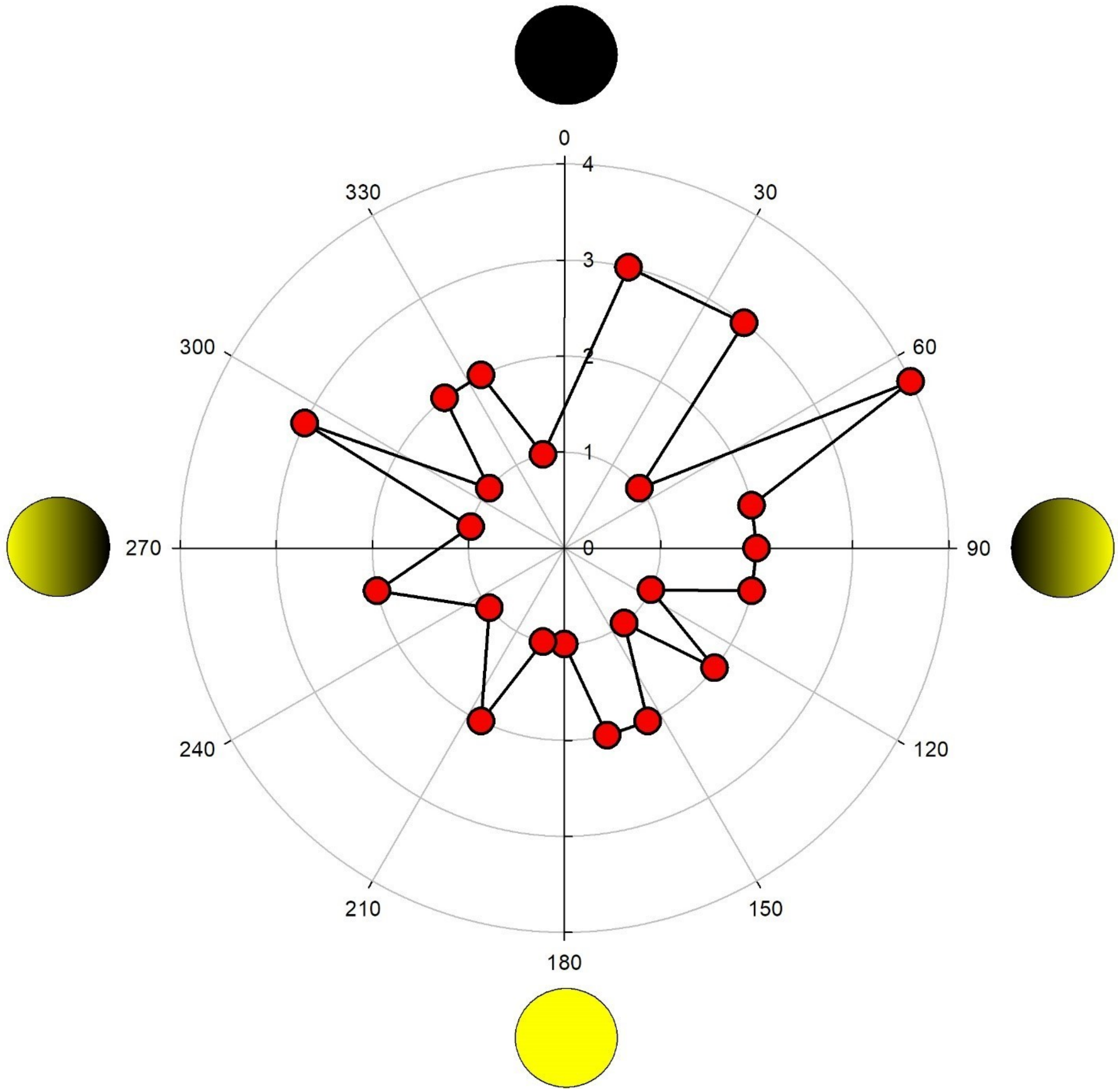


Figure 11. Distribution of hatch dates within a lunar cycle of ‘ōpelu *Decapterus macarellus* (n = 47) captured from Ho‘okena on the west side of Hawai'i Island, Hawai'i, during December 2018 – May 2019. In this figure, the new moon is represented at 0° while the full moon is placed at 180°. The red circles indicated the number of individuals with hatch dates occurring at that point in a lunar cycle during September 2018 – March 2019.

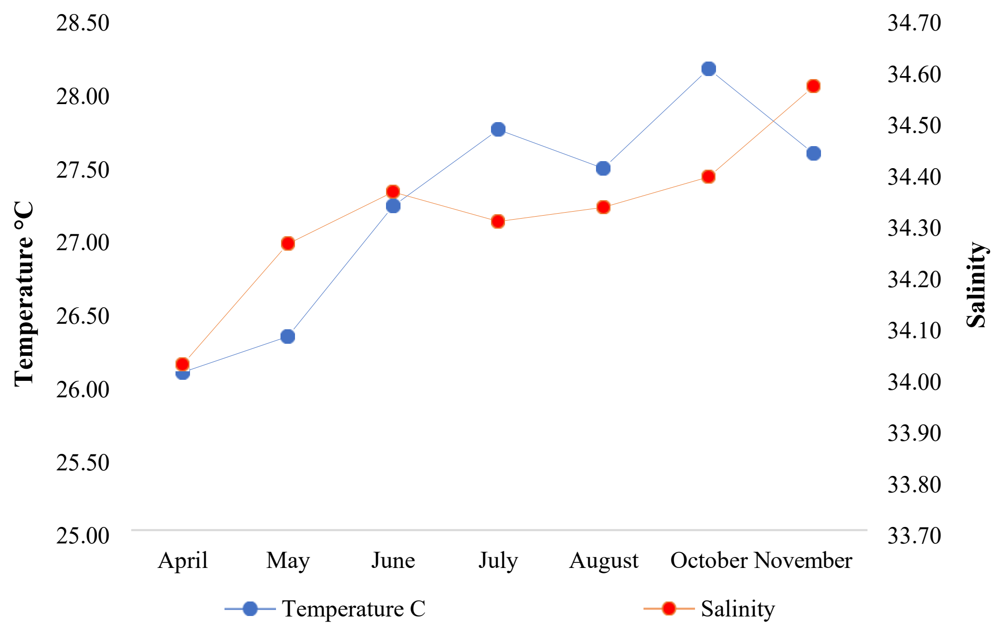


Figure 13. Mean for all depths pooled (0-14.08 m) ocean temperature (°C) and salinity per month. No standard error was greater than 0.08 for temperature and 0.04 for salinity.

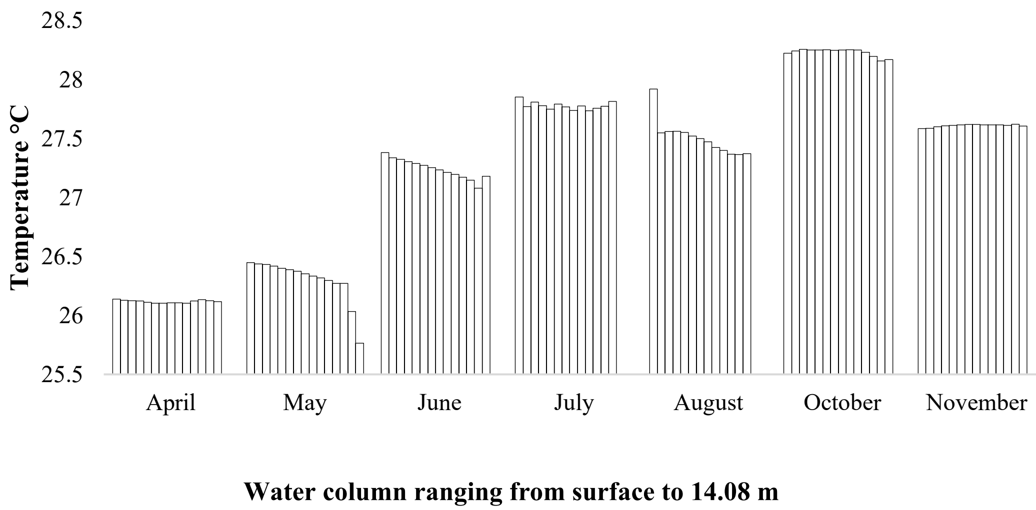


Figure 14. Mean temperature (°C) per month at 0m (surface – 1 meter), 1m (1.0- 1.99), 2m (2.0-2.99), 3m (3.0- 3.99), 4m (4.0-4.99), 5m (5.0-5.99), 6m (6.0-6.99), 7m(7.0-7.99), 8m(8.0-8.99), 9m(9.0-9.99), 10m (10.0-10.99), 11m (11.0-11.99), 12m (12.0-12.99), 13m (13.0-13.99), 14m (14.0-14.8). Temperature ranges from 25.7 and 28.2 °C. The surface temperature in August is likely an error as there was one surface temperature measurement that was significantly higher than all other surface measurements.

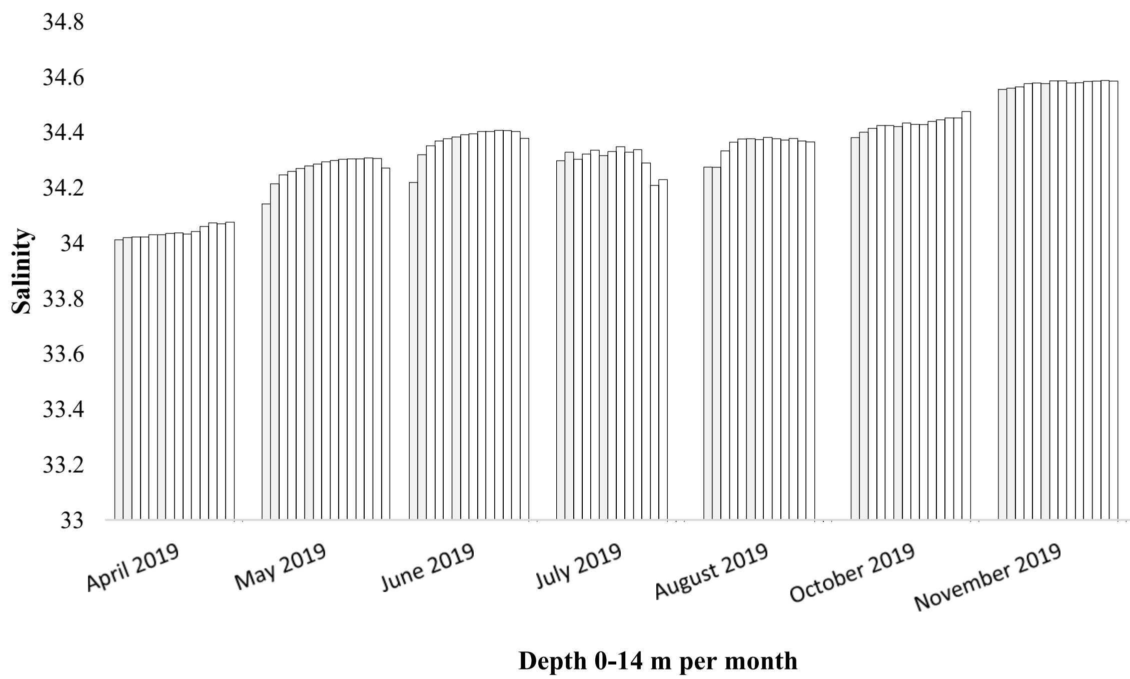


Figure 15. Mean salinity per month at 0m (surface – 1 meter), 1m (1.0- 1.99), 2m (2.0-2.99), 3m (3.0-3.99), 4m (4.0-4.99), 5m (5.0-5.99), 6m (6.0-6.99), 7m(7.0-7.99), 8m(8.0-8.99), 9m(9.0-9.99), 10m (10.0-10.99), 11m (11.0-11.99), 12m (12.0-12.99), 13m (13.0-13.99), 14m (14.0-14.8). July has the most variability whereas the rest of the months sampled seem to have slightly lower salinity on the surface and slightly higher salinity below 1 meter with slight increase about every meter or so.

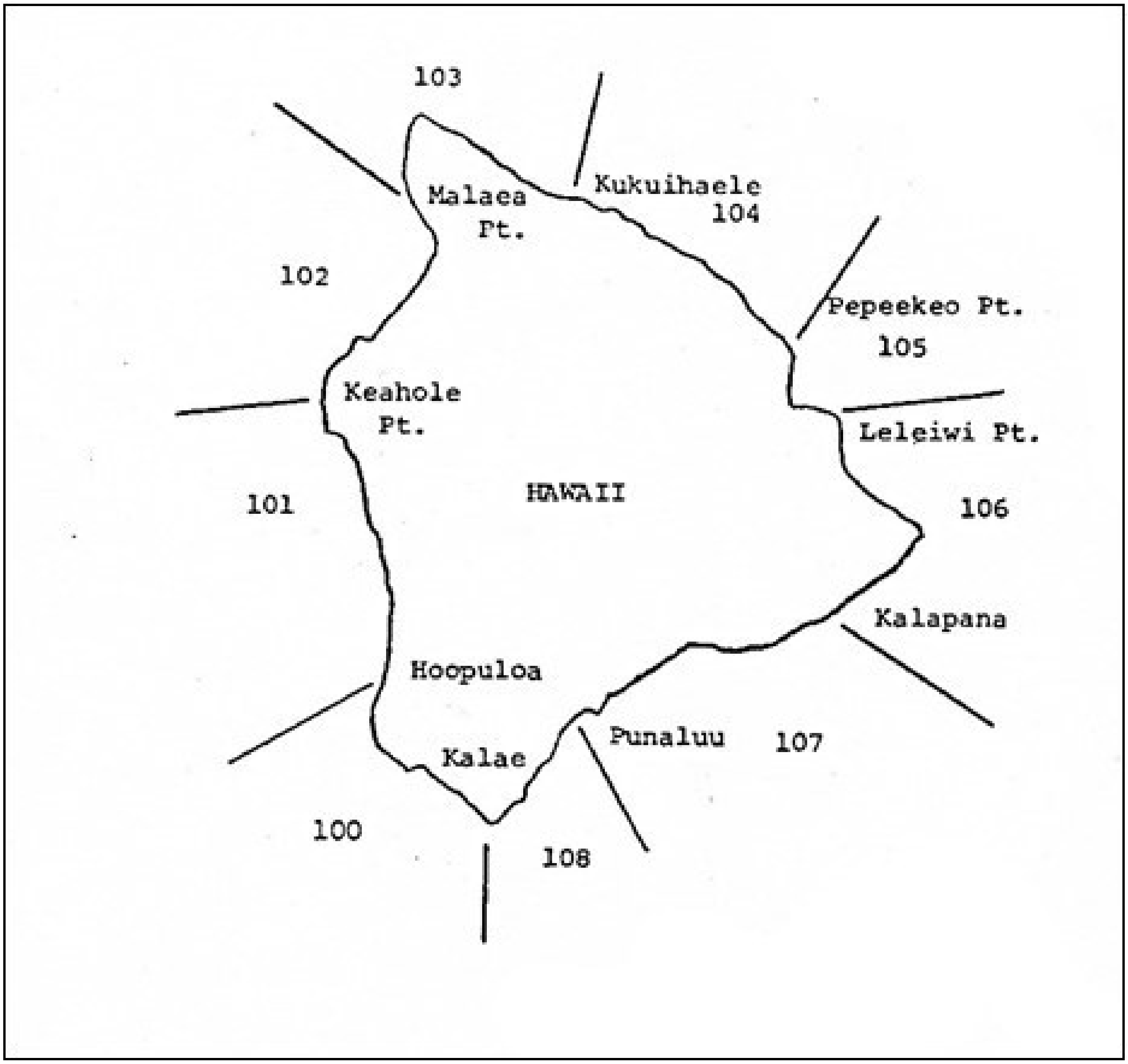


Image 4. (HDAR) Commercial catch reporting zones. Corresponding offshore zones: 100/120; 101/121; 102/122 and so forth

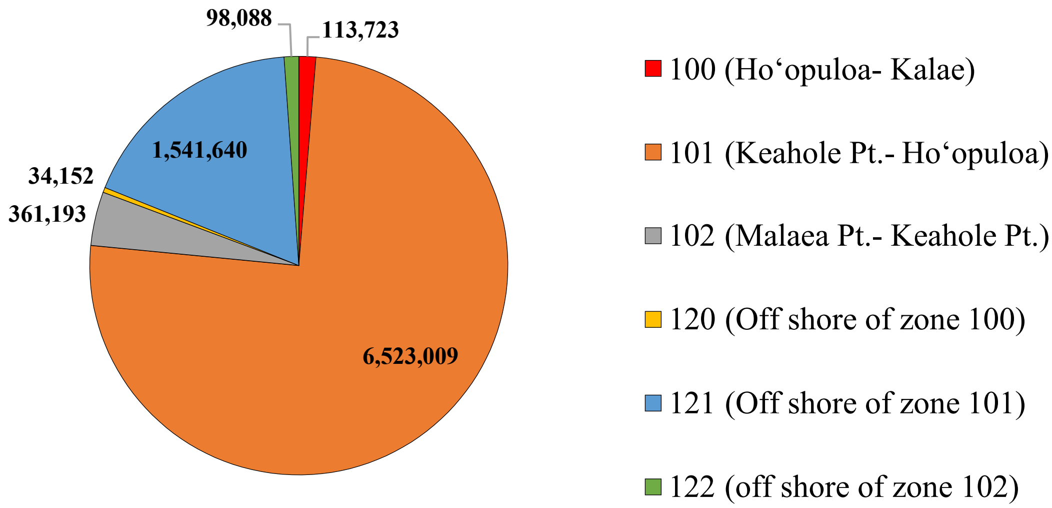


Figure 16. Total ʻōpelu commercially caught in West Hawaiʻi, all methods, 1948 to April 2019. Zones 100, 101, 102 are near shore zones and 120, 121, and 122 are offshore their counter parts. These totals represent only a portion of the catch reported (months when there are 3 or fewer fishers reporting are not shared to protect fisher's privacy).

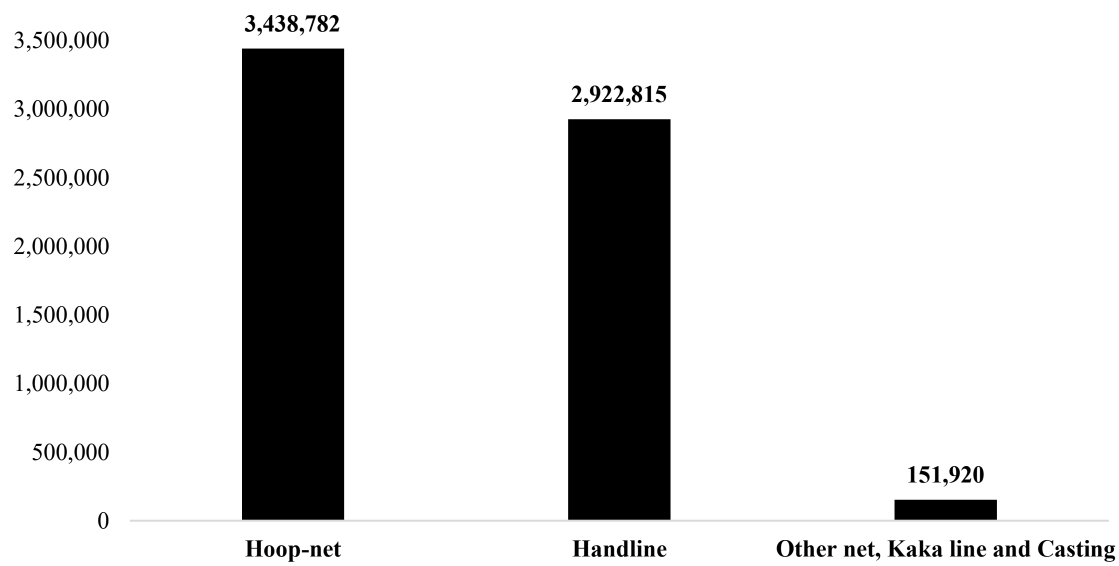


Figure 17. Zone 101 reported catch 1948-2018 by method.

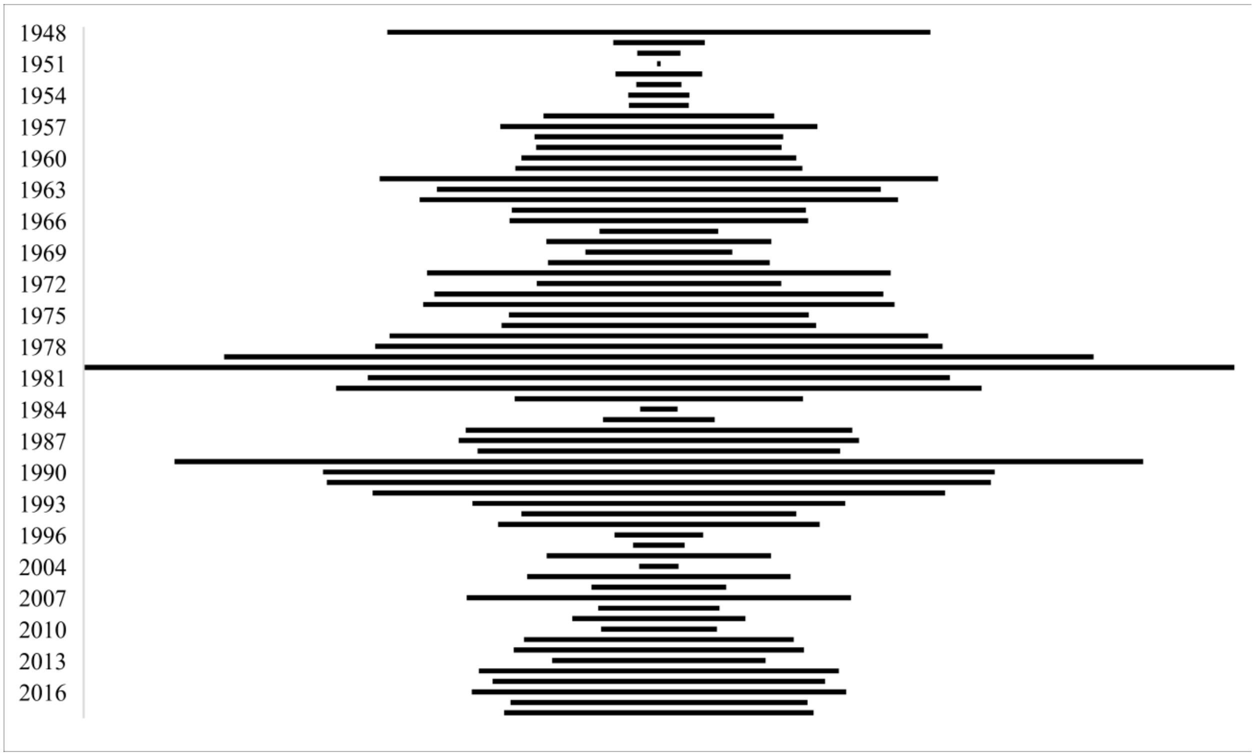


Figure 18. Hoop-net commercially reported ‘ōpelu catch 1948-2018 per year. It appears that this fishery operates on a boom/ bust cycle however it is unknown if CPUE is a factor or if it has to do with ‘ōpelu populations within the fishery.

Image 5. Page 1 Spawning guide created for outreach and education about gonad dissections and methods used

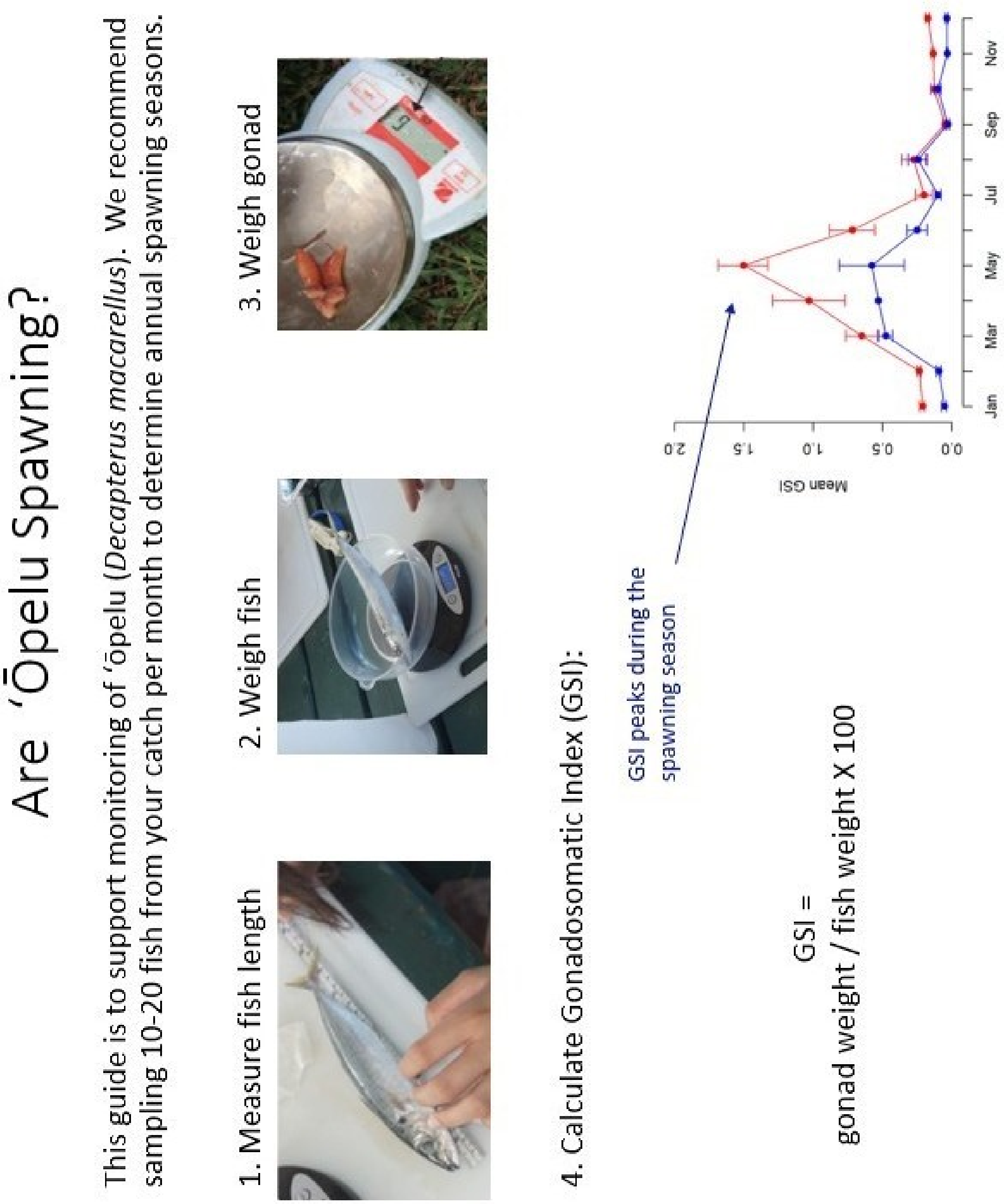


Image 5. Page 2 Spawning guide created for outreach and education about gonad dissections and methods used

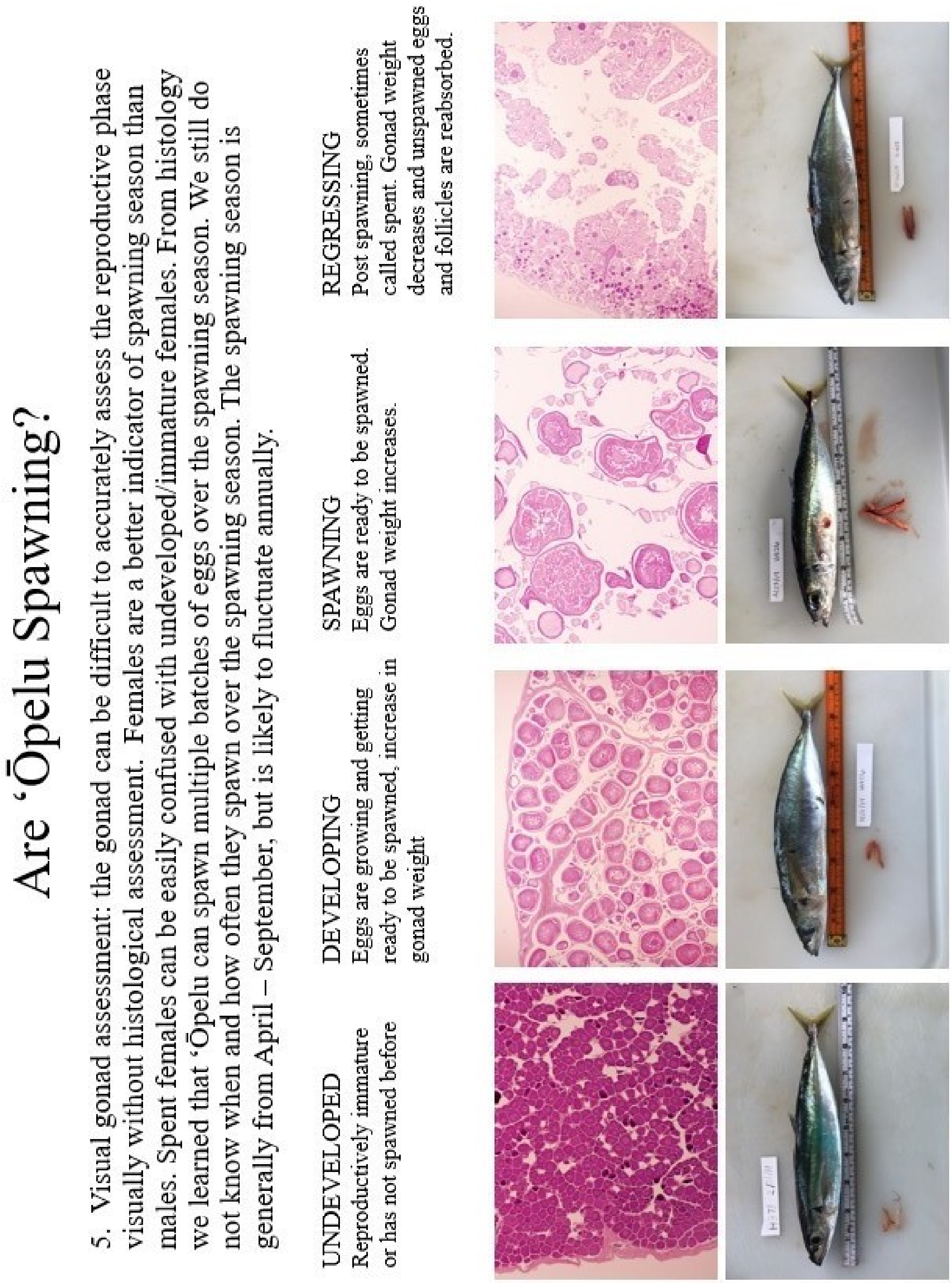


Image 6. Poster created for KUPA for outreach and education

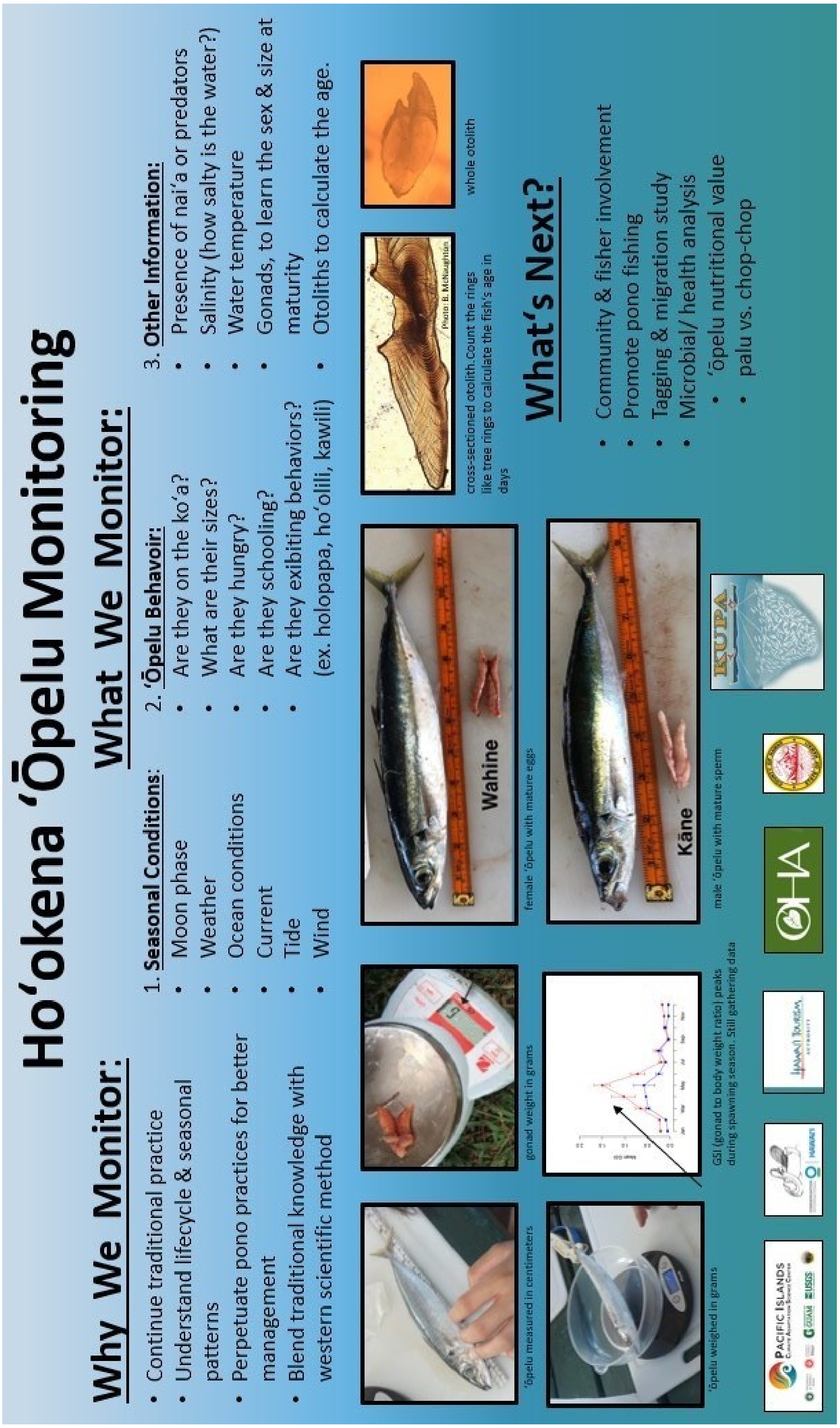


Image 7. Page 1 Methods informational sheet created for KUPA

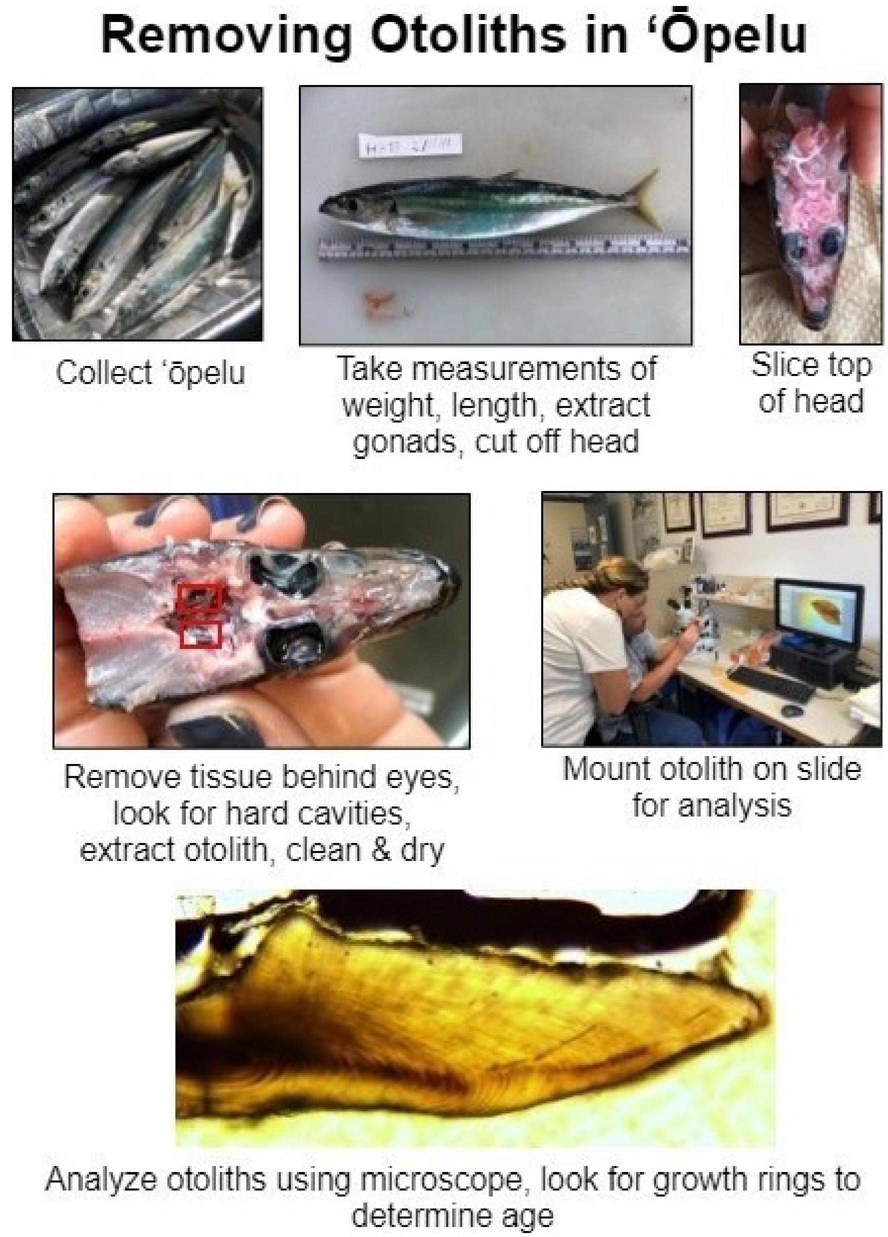


Image 7. Page 2 Methods informational sheet created for KUPA

Words to Know

- ʻŌpelu – Mackerel scad, type of kalo
- ʻŪpena – Fishing net
- Koʻa – Fishing grounds where you can catch ʻōpelu
- Palu – Vegetable based food used to attract ʻōpelu to koʻa
- Hānai – to feed, raise, nourish, caretake
- Kawili – When ʻōpelu are tight and form a solid wall, sometimes moving up and down like a tornado in the water
- Hoʻolili – When ʻōpelu swim up to the top of the water surface, usually when other big fish (ono, mahimahi, ahi, etc.) are chasing them
- Holopapa – When ʻōpelu form a huge school that looks like a land mass moving underwater.
- ʻAu – Current, Kohala & Kaʻū are names of currents used by ʻōpelu fishers.
- Pō Mahina – the moon phase
- Mālama – the lunar month
- Spawning – When fish release or deposit eggs
- Gonad – reproductive organ that fish use to spawn
- Dissection – To cut open & look at different parts of the fish
- Fork Length – The length of the fish from snout to the fork in the anal tail
- Otolith – Inner ear bone of a fish used to sense balance and movement