Aerial survey as a tool for understanding bigeye scad (*Selar crumenophthalmus*) dynamics around the island of O'ahu, Hawai'i

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Abstract

The bigeye scad (*Selar crumenophthalmus*) supports one of the most productive near-shore fisheries in Hawai'i. Fishing boats frequently work in tandem with spotter planes to efficiently target bigeye scad schools. These spotter planes provide the means for a fishery-independent estimate of abundance based on direct observation, which may prove more sensitive to population trends than traditional estimates based on reported commercial catch and effort. An experienced spotter pilot was utilized to survey the biomass of bigeye scad schools surrounding the island of O'ahu for the 2015–2016 fishing season. The survey data were then used to create fishery-independent indices of apparent abundance at varying temporal and spatial scales to compare with fishery-dependent indices generated from commercial catch and effort data from net gears. The survey data also allowed for a better understanding of bigeye scad spatial and temporal patterns around O'ahu. Trends between fishery-independent and fishery-dependent indices of abundance were similar. The western region of O'ahu has the highest index value, exceeding each of the other three regions by two to five times. A clear temporal trend was also observed; indices increased from the lowest values during the beginning of the fishing season (November–January) to the highest values during the peak season (May–July). Our findings suggest that commercial catch and effort data are adequate to track trends in abundance of bigeye scad and inform management decisions.

Key Words

Abundance Index; Fishery-independent; Hyperstability; Akule; Coastal Pelagic

1. Introduction

Fishery-dependent catch and effort data are commonly utilized to generate abundance indices for fish stocks based on the assumption that catch per unit effort (CPUE) is proportional to abundance. However, it has long been argued CPUE may not accurately reflect true changes in abundance (Beverton and Holt 1957), and a more recent analysis supports this argument (Harley et al. 2001). Hilborn and Walters (1992) discuss an alternative relationship between CPUE and abundance called hyperstability, where CPUE remains high as abundance decreases. Pelagic schooling species are especially prone to hyperstability; fewer schools are present as abundance declines, yet school densities remain preserved, and therefore fishermen can harvest consistent catches (Brierley and Cox 2015). Basing fishery management decisions on the false assumption that catch is proportional to abundance can contribute to declining fish stocks (Rose and Kulka 1999).

Bigeye scads (*Selar crumenophthalmus*) are a schooling coastal pelagic species and have a circumtropical distribution throughout the Atlantic, Indian, and Pacific Oceans, including the warm coastal waters of all the Hawaiian Islands. In Hawai'i, bigeye scads are commonly referred to as "akule" when their total length exceeds 22 cm; shorter individuals are called "halalū" (Iwai et al. 1996). We use this convention throughout this paper and use the term akule only when referring exclusively to large bigeye scad.

Bigeye scad has a high growth rate (K = 0.21/month) signifying high productivity (Kawamoto 1973) and reaches sexual maturity at a standard length of about 20 cm (Clarke and Privitera 1995). Captive males and females reach maturity at a fork length of 19 cm and 25 cm, respectively (Iwai et al. 1996). Weng and Sibert (2000) estimated sexual maturity occurs after 7 months based on a von-Bertalanffy growth curve fit to length data produced from tag-recapture experiments by Kawamoto (1973). The months of April - October are the main spawning period (Clarke and Privitera 1995). Recently recruited schools first appear in July and persist through December, suggesting a 4-month (April–July) ichthyoplankton growing phase (Kawamoto 1973). Bigeye scad raised in captivity also spawn in accordance to these natural patterns during their first year. After the initial year, the broodstock spawned repeatedly (5-10 times) throughout each of the following two years (Iwai et al. 1996). Captive bigeye scads grew to a mean total length of 13.24 cm 141 days post hatch (Welch et al. 2013). The estimated annual mortality fraction for bigeye scad within Hawai'i is 99.3%, though these fish may survive over two years (Kawamoto 1973).

Bigeye scad represents the largest proportion of total landings by weight among species listed in the Fishery Ecosystem Action Plan (WPRFMC 2009) for the Hawaiian Archipelago. The most effective method used to commercially harvest bigeye scad utilizes surround net fishing gear. Gill nets are most often used and less labor intensive than deploying fence (bag) nets which require SCUBA divers to close the nets (See Kazama 1997 for fishing techniques). These operations are often performed in coordination with spotter planes because the planes are far more efficient in locating schools of fish than are boats. Each morning, bigeye scad schools form in the coastal areas surrounding O'ahu. The spotter plane relays the location and estimated size of these schools to the fishermen who rely on the pilot's accurate biomass estimates to determine the most advantageous school to pursue. Fishermen often target a school in the morning that was spotted the previous day. The same fish aggregation might also be fished multiple times, over many days, as it repeatedly reforms. These accounts are supported by a tag and release study that found little movement among individual bigeye scad around O'ahu and no recaptures on neighboring islands (Kawamoto 1973).

As specified by the Magnuson-Stevens Fishery Conservation Reauthorization Act of 2006, fish species listed in Fishery Ecosystem Action Plans (FEP) are required to have reference points based on the best available science (MSRA 2007). A stock assessment for bigeye scad was previously conducted in 2000, using historical catch and effort information from the state of Hawai'i commercial reporting database (Weng and Sibert 2000), and therefore bigeye scad reference points were calculated using fishery-dependent data. Weng and Sibert (2000) applied a surplus production model (Schaefer 1954) and determined bigeye scad has undergone light to moderate exploitation and suggests that yearly catch fluctuations are more dependent on social pressures dictating effort rather than population abundance. However, should assumptions about catchability being proportional to bigeye scad abundance not hold, this conclusion may be unjustified. Despite being heavily fished, bigeye scad was removed from the FEP as a management unit species and placed into an ecosystem component categorization in 2018 (NMFS 2019). Although the stock status of bigeye scad is not currently required to be assessed relative to established reference points, they must still be monitored. The potential for hyperstability warrants exploring whether fishery-independent trends in abundance differ from current sources of information, and if monitoring of populations in the future should be conducted using fishery-independent approaches, or continue based on commercial catch and effort information.

Aerial surveys provide a method to estimate abundance of marine species independent of a fishery and thus provide a time series of data to compare indices of abundance with fishery-dependent sources of information. The use of aerial spotting planes has provided a means for direct observations of many marine species found at or near the ocean surface. This method of surveillance has been largely utilized in scientific surveys for estimating population sizes and distributions of marine animals spanning many taxonomic groups, such as turtles (Marsh and Saalfeld 1989), dolphins (Slooten et al. 2004), dugongs (Pollock et al. 2006), sharks (Cliff et al. 2007), tunas (Basson and Farley 2014), and coastal pelagic species (Lynn et al. 2014).

This study describes the results from a fishery-independent, qualitative aerial survey of bigeye scad apparent abundance, defined "…as the abundance as affected by availability, or the absolute number of fish accessible to a fishery (Marr 1951)," around the island of O'ahu in the Hawaiian Islands. The first objective of our study was to compare the index of apparent abundance from a fishery-independent aerial survey to a fishery-dependent index based on catch records in the commercial fishery and assess the potential for bigeye scad hyperstability. We analyzed the index across different spatial and temporal scales to determine differences due to scale and to improve future sampling design. The second objective was to describe spatial and temporal patterns in bigeye scad dynamics and reveal local distribution, general movement, and timing of spawning around O'ahu. This information can be used by managers to inform best approaches for future monitoring of bigeye scad relative apparent abundance and better understand movement and recruitment dynamics within the Hawaiian Islands.

2. Materials and Methods

Bigeye scad represent an ideal test species because of their predictable near-shore schooling behavior each morning around the island of O'ahu. A spotter pilot was chartered to collect data on the number and biomass of bigeye scad schools around O'ahu over the course of 12 months from November 2015 to October 2016 (PIFSC 2019a). A single pilot was used to limit possible bias introduced by varying spotting ability (Lo et al. 1992). Ten flights were scheduled each month based on a power analysis using data from a 2014 pilot project to detect monthly differences observed from that dataset at a significant level of 0.05 and power of 0.8 (Wiley et al. 2015). Each week of the year was randomly assigned 2 or 3 flights, such that during every month, 10 flights were scheduled. The pilot conducted a total of 117 aerial surveys during the survey period, missing 3 scheduled flights in December due to restrictions in available airspace.

During each flight, the pilot circled the entire island of O'ahu either clockwise or counterclockwise (n=26 and 91, respectively) depending on weather conditions (mainly wind). The choice of direction was left to the discretion of the pilot to ensure safety. Flights occurred within 3 km of the coastline at altitudes ranging from 150 to 350 m during early morning and afternoon hours after the schools of bigeye scads formed. An onboard GPS unit (Garmin GPSMAP 76, Garmin Ltd[1]) recorded the tracks and times for every flight. The pilot took a picture of each observed school with an iPhone 4 (Apple Inc) capable of time and GPS stamping. Pictures provided a means to verify school location and reference for the pilot to double check biomass estimates. Additionally, time spotted, life stage (akule, halalū, or mixed), estimated biomass (lbs), and cloud cover (presence or absence) were recorded by the pilot for each school. Biomass was estimated by using landmarks on the ground, such as buildings and cars, to gauge the area of each school. The pilot then incorporated local knowledge of bottom substrate and depth of the area to determine the estimated biomass for the school. Distinct akule schools were identified by a darker color as the larger more experienced fish swim in tighter formations. More synchronous and organized swimming behavior is also indicative of larger akule.

The flight paths from the onboard GPS unit were loaded into ArcGIS software (Environmental Systems Research Institute, Version 10.3.1) to view area searched (Figure 1). The Honolulu International Airport and resulting air traffic hindered searching along the

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southern region, specifically the western portion of grid 400 and the eastern portion of grid 401. As such, unsearchable areas, including 14.73 square miles from grid 400 (including Pearl Harbor) and 24.81 square miles from grid 401, were removed from the analysis. Additionally, the area surrounding the military base on the peninsula between grid 407 and 408 could not be searched. This resulted in the removal of 6.26 square miles from grid 407 and 7.66 square miles from grid 408. The GPS points from the pictures were also extracted and loaded into ArcGIS to provide location of spotted schools.

For each flight, a fishery-independent index of apparent abundance was calculated by dividing the total estimated biomass of all sighted schools by the total area searched for 3 distinct spatial scales: commercial fishing grid (400–409), region (north, east, south, and west), and whole island. These daily values were then averaged over 3 temporal scales (monthly, seasonally, and whole year) to produce the final survey indices of apparent abundance. Seasons consisted of the beginning months (November–January), middle months (February–April), peak months (May–July), and end months (August–October) of the fishing season. Differences between regional indices over the whole year and between seasonal indices over the whole island were each assessed using a Kruskal-Wallis test (Kruskal and Wallis 1952) as data were not normally distributed, and then compared using Dunn *post hoc* comparisons with significance values adjusted by the Bonferroni correction for multiple tests. (Dunn 1964; both using IBM SPSS Statistics version 25.0).

Commercial catch and effort data over the same time period and search areas as the aerial survey were acquired from Hawai'i's Division of Aquatic Resources (DAR) commercial catch database (PIFSC 2017) to compare the fishery-independent index of apparent abundance with the fishery-dependent index historically used. Catch of bigeye scad was reported from both hook and line gears and net gears, which differ in catchability. As such, the fishery-dependent index (hereafter referred to as the catch index) was limited to net gears only (fence, gill, lay, and cross nets), which were all boat-based and accounted for nearly 75% of the total catch during the time period of the aerial survey. Net gears are reported as a single gear code in the database so distinguishing among types of net gears was not possible. The catch index was calculated as the average of individual pounds of catch of bigeye scad per hour of fishing with nets in the water. The catch indices were compared to the corresponding indices from the aerial survey (hereafter referred to as the survey index) following the same spatiotemporal scales. Due to fishermen confidentiality requirements, direct comparisons between the catch and survey indices could only be shown by region over the entire year and monthly over the whole island. Comparisons combining finer spatial scales were restricted to Pearson correlations calculated using ‘cor’ in R version 3.6.3 (R Core Team 2020).

3. Results

3.1 Aerial survey

The pilot spotted a total of 854 schools of bigeye scad surrounding the island of O'ahu during the survey period. Estimated school sizes ranged from 500 to 60,000 lbs, with a mean size of 7,702 (SE=230) lbs. During the beginning season (November–January), 27 flights resulted in a mean of 5.4 (SE=0.38) schools and 48,374 (SE=5,035) lbs spotted per trip. During the middle season (February–April), 30 flights resulted in a mean of 6.1 (SE=0.57) schools and 52,767 (SE=6,701) lbs spotted per trip. During the peak season (May–July), 30 flights resulted in a mean of 9.9 (SE=0.66) schools and 72,243 (SE=4,802) lbs spotted per trip. During the end season (August–October), 30 flights resulted in a mean of 7.6 (SE=0.40) schools and 54,750 (SE=4,618) lbs spotted per trip. Seasonal survey indices for each commercial reporting grid are provided in Figure 2.

Bigeye scad survey indices were highest in the western region (n=117 for each region). The mean survey index across the year for the western region ($\bar{x}$=483 lbs/mi^2; SE=30 lbs/mi^2) exceeded the values for each of the other regions by 2 to over 5 times. The southern region ($\bar{x}$=177 lbs/mi^2; SE=15 lbs/mi^2) had the next highest survey index, followed by the eastern region ($\bar{x}$=123 lbs/mi^2; SE=12 lbs/mi^2), and finally the northern region ($\bar{x}$=88 lbs/mi^2; SE=12 lbs/mi^2). Differences between index values across regions ($p < 0.01$) over the whole year was significant. The western region was significantly different than each of the other regions ($p < 0.01$) while the southern region differed from the northern region ($p < 0.01$).

Survey indices had similar temporal patterns over the course of the year with one exception for the western region (Figure 3). Each of the other regions had their lowest index values during the beginning season. Following the beginning season low point, indices then increased into the middle part of the fishing season, continued to increase into the peak months, and decreased in the end of the fishing season. The northern region index increased nearly 5.5 times from the beginning season to peak season. The southern and eastern region indices increased 2.5 and nearly 3 times, respectively. Conversely, the western region survey indices were highest during the beginning season, dropped during the middle season, remained consistent during the peak season, and then dropped again during the end season. The seasonal index values for the whole island (n=27 beginning; n=30 middle, peak, and end) varied significantly ($p < 0.01$). The peak season indices ($\bar{x}$=253 lbs/mi^2; SE=17 lbs/mi^2) were different than both the beginning and middle season indices ($\bar{x}$=170 lbs/mi^2; SE=17 lbs/mi^2; $p < 0.01$ and

$\bar{x}$=185 lbs/mi^2; SE=23 lbs/mi^2; $p < 0.01$, respectively), while end season indices ($\bar{x}$=228 lbs/mi^2; SE=8 lbs/mi^2; $p < 0.05$) differed from those in the beginning season.

The pilot's ability to decipher between life stages from the air allowed for a temporal comparison of apparent biomass across life stage (Figure 4). Schools that could be clearly classified as either akule or halalū were included in this figure separately (n=548 and 134, respectively), while mixed schools (n=172) were included in the total biomass estimates along with akule and halalū. Values for life stages are separate from the survey indices and expressed as mean daily biomass (lbs/trip) for the entire island of O'ahu indicating available biomass to the fishery. Halalū appear to dominate during November and December. Halalū abundance dropped continually over the next 3 months, and minimal numbers were observed from April through August. Although still present within mixed schools, distinct halalū schools first appeared again in September. Akule and halalū have a clear inverse relationship throughout the year with akule biomass peaking in the summer months. The daily number of schools sighted around O'ahu is also provided and tracks similarly with biomass throughout the year.

3.2 Comparison to fishery catch data

Island-wide survey indices were generally similar to catch indices by month but revealed some differences (Figure 5). The survey index was positively correlated (ρ=0.62) to the catch index during the beginning and middle fishing season matching the decline in November and the increasing trend into May. The survey index was not correlated with the catch index thereafter (ρ=-0.1), peaking in June, which was later than the peak in the catch index, and remaining steady through October. When analyzed by season correlation between the two indices was ρ=0.46. Greater declines in the survey index compared to the catch index following the opening of the fishing season (November to December) and from January to February resulted in a middle season increase over the early season of only 9% for the survey index compared to 27% for the catch index. The increase from February to June in the survey index resulted in a peak season increase of 37% over the middle season, whereas the catch index decreased between these seasons by 2.6%. The June peak for the survey contrasted with the lack of decline in October to result in an end season decrease of 10% over the peak season, which was comparable to the decline of 8% for the catch index during the same period.

Region-specific differences between the survey and catch indices were also identified, and were most noticeable in the western region (Figure 6). Data from the northern region were not included in the figure due to confidentiality in the catch data. Variability across regions was greater for the survey index (CV = 83%) than for the catch index (CV = 24%) due to a higher value in the western part of the island compared to other regions for the survey index, though the relative patterns were similar (ρ=0.62). Catch data from specific management areas were also confidential so values cannot be shown. However, the correlation between the catch index and survey index across the management areas also suggests that patterns were similar (ρ=0.79). Region-season differences could not be shown for catch data, and, with the exception of the northern region (ρ=0.98), patterns were not strongly correlated across season (ρ_{south}=0.4, ρ_{west}=0.23, ρ_{east}=0.58) with the patterns from the aerial survey.

4. Discussion

The use of fishery-independent abundance estimates for bigeye scad offers a comparable methodology to abundance estimates derived from commercial catch and effort data, providing an additional tool to help decipher possible trends in abundance and identify biases and limitations within either of the two approaches. Barnes et al. (1992) suggested that an integrated approach for stock assessment combining data from fishery-independent and fishery-dependent sources will best meet future management needs. Such an approach will alleviate the inherent weaknesses of any single method and provide a more robust estimate of patterns in abundance.

Our study shows that the overall fishery-independent index of apparent abundance around O'ahu did not greatly differ from the fishery-dependent index. When indices were compared at smaller spatial and temporal units, stronger correlations were revealed. The survey index showed a greater value of bigeye scad apparent abundance during the peak fishing season in the western region than did the catch index. This is likely due to the western region having the greatest available biomass and the survey being able to identify the majority of fish within a school as opposed to fishing, which captures a smaller subset of the fish in that school. Therefore, the survey is able to assess a larger amount of information than fishing, though overall trends in the information were still similar across management areas between approaches. Additionally, the commercial fishery must adhere to market trends as saturation results in pauses to fishing effort. This may limit efficiencies during the peak season where the survey index indicated a peak in available abundance not seen in the catch index. Given that the 2000 stock assessment indicated light to moderate fishing pressure (Weng and Sibert 2000), it is likely that current fishing is not able to generate sufficient pressure to cause hyperstability. Tracking the number of bigeye scad schools further supports the lack of hyperstability as school numbers were maintained throughout the year and tracked well with biomass (Pitcher 1995). As such, it appears that catch and effort data is a suitable source to assess trends in bigeye scad abundance.

Historical bigeye scad commercial fishing records around O'ahu indicate that effort is highly concentrated in the western and southern inshore waters (Weng and Sibert 2000). These waters are the most protected from large winter swells and continuous trade winds (Stopa et al. 2011). Such conditions are suitable for safer and more efficient fishing operations. Indices of apparent abundance derived from our aerial survey illustrate greater abundance of bigeye scad along these same regions (especially the west). Thus, fishing effort aligns not only with favorable ocean conditions but also with greater availability of fish.

This yearlong study illustrates a temporal pattern for bigeye scad at various life stages surrounding O'ahu. The smaller halalū dominate distinct schools from November through December when akule numbers were at their lowest. These months directly follow the regulation restricting netting of bigeye scad under the total length of 21.6 cm (8.5 in) from July through October. Halalū abundance drops following December as recruitment declines (Kawamoto 1973), and smaller fish are predated and harvested or mature into akule. Distinct halalū schools are largely absent around O'ahu beginning in April, which Kawamoto (1973) suggested marks the beginning of the main spawning season for akule based on mature or spent gonads observed through November. Aerial estimated akule abundance also dominates the population during the spawning period, lasting through October. The presence of these fish supports the claim of a sexually mature population (Clark and Privitera 1995). The 4-month ichthyoplanktonic life stage proposed by Kawamoto (1973) was based on observed halalū schools returning in July. Our aerial survey did not detect distinct halalū schools until September; halalū were still present but were mixed with akule.

The July halalū run is widely known among fishermen as they line the harbors and shorelines each year to catch the small fish. Our study observed a 2-month delay to this anticipated event for the 2016 season, with an influx of distinct halalū schools in September. However, this discrepancy might also be explained by the pilot's difficultly to clearly distinguish unique halalū schools, masking the actual start of the run with mixed schools present during this time. Anecdotal evidence from a commercial bigeye scad fisherman along the west coast of O'ahu supports a normal July 2016 run for halalū (C. Jellings, commercial fishermen, pers. comm.).

November 1st marks the opening of the fishery when commercial fishermen deploy fence nets. This method is more labor intensive but catches a much greater percentage of the school and allows for the catch of the smaller halalū by using 3.8 cm (1.5 in) nylon mesh netting. The fence net is deployed with a skiff around the entire school and used in combination with a bag net. Once the school is fenced off, SCUBA divers enter the water and secure the bag between sections of the net on the down-current. Divers then work the net closed to funnel fish into the bag net which is lifted up and secured to the fishing vessel. Fishermen often stake out claims to fish areas the night before resulting in heavy effort when this fishery opens. However, these nets are not often used later in the season as the halalū grow and become accessible using gill nets. Gill nets are deployed around the school by skiffs and then fish are scared outward by the fishing vessel to become entangled. Gill nets capture a smaller fraction of the school as fish can escape below the nets.

Commercial catch reported to DAR shows November to have the highest month's catch, aligning with the opening of surround net gear. Additionally, a larger decline was observed in the survey index following the opening month of November. Assuming halalū were not more likely missed by the pilot, this suggests the decline in halalū may be more prominent during this time than what is captured by the catch data. Conversely, the catch index showed a steeper decline during the end of the fishing season than the survey index. If hyperstability was occurring, we would expect the catch index to remain high as the survey index declines. Thus, there is no evidence for hyperstability within the year.

Aerial spotter abundance estimates offer distinct advantages over catch and effort evaluation. Catch per unit effort can be maintained even as actual fish abundance decreases (Harley et al. 2001), especially for schooling pelagic species (Pitcher 1995) such as bigeye scad. Data attained from commercial catch reports can also be influenced by market demand, hold capacity, or processing capacity (Lo et al. 1992). In contrast, fish spotters may report larger portions of observed schools and biomass, as was the case comparing our survey index to the catch index. Additionally, aerial spotter efficiency is less likely to be influenced by technological advances over time as schools must still be located visually while flying at low speed and low altitude. Commercial fishing efficiency has improved greatly due to technological improvements to nets, use of aerial spotters, and use of SCUBA diving gear (Kazama 1977). Consequently, resulting CPUE increases may confound long-term comparisons due to catchability changes. However, aerial survey accuracy may be influenced by improved skill of pilots over time or introduction of new pilots (Lo et al. 1992). Longer term aerial surveys must account for these potential changes to maintain their accuracy (Barnes et al. 1992).

Bigeye scad aerial surveys were modeled after studies on northern anchovies and Pacific sardines in Californian waters (Squire 1972; Barnes et al. 1992; Lo et al. 1992). These species are similar in size, share a comparable ecological niche, and also school in large numbers near the ocean's surface. Squire (1972) assigned aerial observations of biomass to zones that outlined important geographical areas in which fish were commonly encountered. An index of abundance was then determined as tons sighted per zonal area. Similarly, commercial fishing grids have been assigned to the waters surrounding O'ahu for reporting fishing landings, which serve as the zones for this study.

There remain limitations to fishery-independent surveys in general, and to our approach specifically. Aerial survey biomass estimates introduce unique problems when used to estimate abundance. Possible sources of error include environmental conditions which may hinder detectability (e.g., cloud cover, glare, water turbidity, wind, and wave height), animals too deep to spot, and the skill of the pilot spotting schools and estimating size. Additional bias may be introduced when multiple pilots are used (Lo et al. 1992). There also remain practical limitations such as cost and effort to regularly deploy and maintain fishery-independent observations.

The specific limitations to our yearlong study are primarily temporal and spatial. The representativeness of our aerial survey, and comparison to fishery catch data, is dependent on how representative 2016 was in comparison to other years. Catches and number of licenses in 2016 were not noticeably different than in years since 2010 for all fishery sectors (WPRFMC 2019). Comparing the 2016 commercial data to years since 2010 showed no noticeable anomalies with the 2016 data. Nonetheless, extending our study to more than one year would more completely indicate whether patterns observed in 2016 are normative. Our conclusions are also limited to the population around O’ahu as the additional cost required to search other islands was not feasible for our study. Catches in the western and southern waters around O’ahu have high catch and high CPUE within the Hawaiian Islands that are comparable to areas of the Big Island, Kauai, and the Maui-Nui region (Weng and Sibert 2000). Consequently, the scale of fishery removals is similar between O’ahu and other regions, although trends in estimates of fishery-independent abundance could be different among island groups given that each island within the Hawaiian Islands has different environmental and anthropogenic forces influencing fish communities (Jokiel 2008).

Assuming our results generally hold for past and future years, any future work on O’ahu should focus on the western region around O'ahu, as this region is generally well populated by bigeye scad throughout the year. Research done during the peak fishing season could be done throughout the island as we found bigeye scad tend to distribute themselves around the island during this period. Any studies looking at changes in distribution could emphasize the fringe regions to determine the extent of bigeye scad distribution, but it is clear from our study that bigeye scad also populate areas that are not commonly fished. Continuation of fishery-independent measures could be done to ensure results for this one year of sampling are not overly optimistic compared to other years or other neighboring islands. However, given the limited pressure fishing has been suggested to have on the population (Weng and Sibert 2000), monitoring of fishery-dependent data is likely adequate at this time.

5. Acknowledgements

Funding for this project was provided by the Western Pacific Regional Fishery Management Council through the NOAA Cooperative Research Fund grant number NA15NMF4410008. This work would not have been possible without the enormous effort from the pilot Simeon Ivanov and the fishing operations of Kaipo Miller and Island Wide Fishing. Mahalo for all your help and letting me tag along and learn from your extensive fishing knowledge. Finally, we thank the three anonymous reviewers for their careful critiques and helpful suggestions to improve this manuscript. The scientific results and conclusions, as well as any views or opinions expressed

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7. Figures

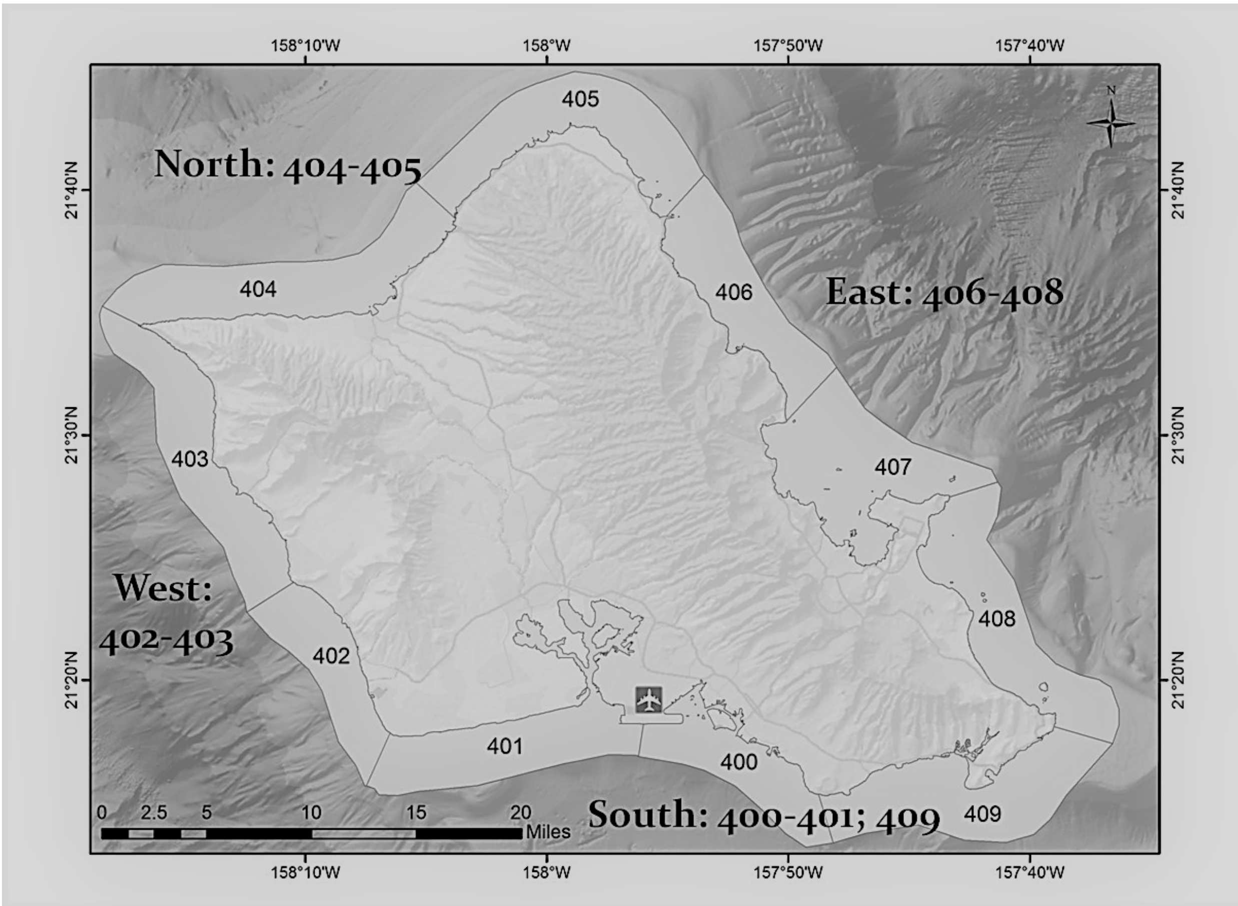

Figure 1. Map of O'ahu displaying the numbered commercial fishing grid areas and the region (shoreline) to which they belong. Airplane marker represents the location of the Honolulu International Airport.

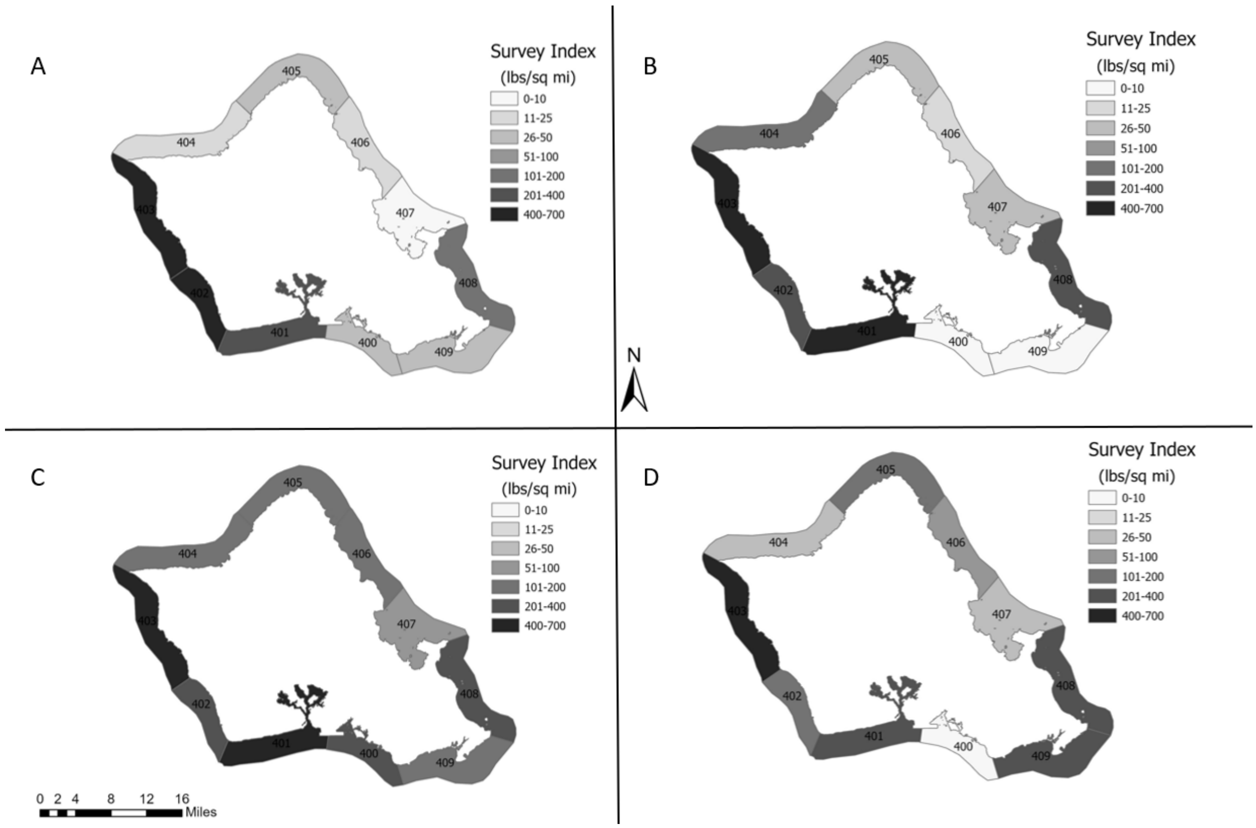

Figure 2. Aerial abundance indices – biomass estimate (lbs) divided by search area (mi^2) – for bigeye scad surrounding the island of O'ahu from November 2015 – October 2016 separated by season: (A) Beginning (Nov–Jan), (B) Middle (Feb–April), (C) Peak (May–July), (D) End (Aug–Oct). Numbered grids represent Hawai'i commercial fishing grids.

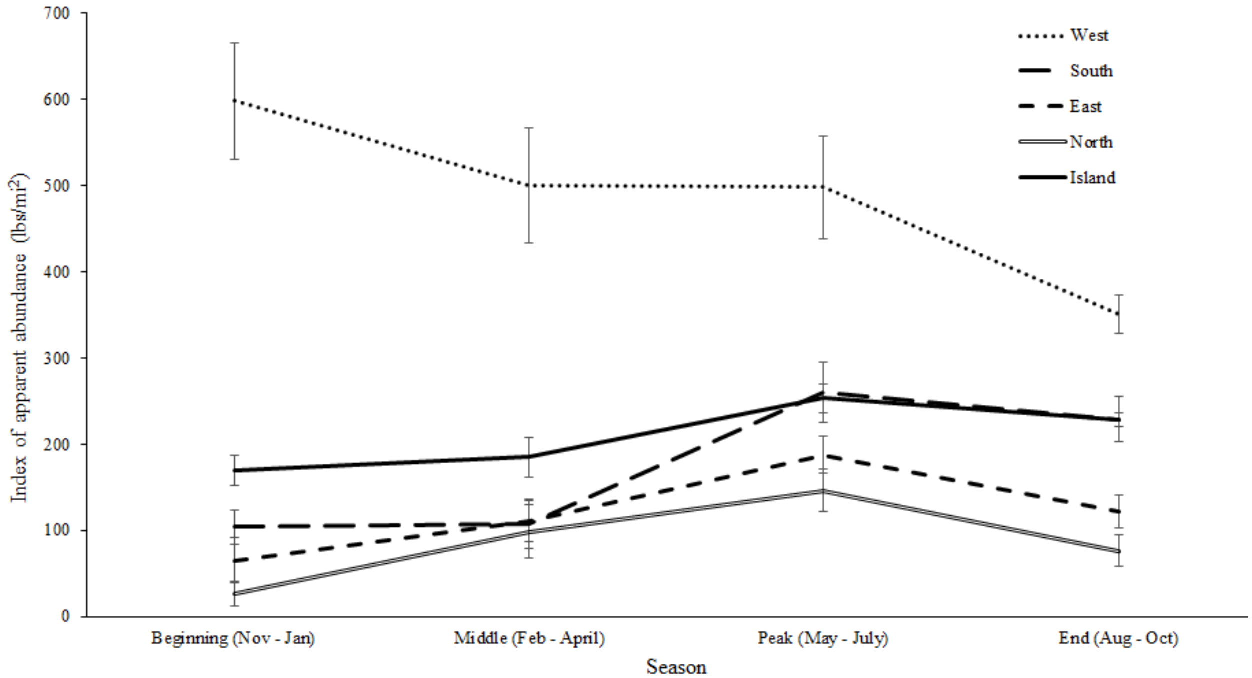

Figure 3. Mean index of apparent abundance – biomass estimate (lbs) divided by search area (mi^2) – for bigeye scad by season and region surrounding the island of O'ahu. Error bars represent one standard error from the mean.

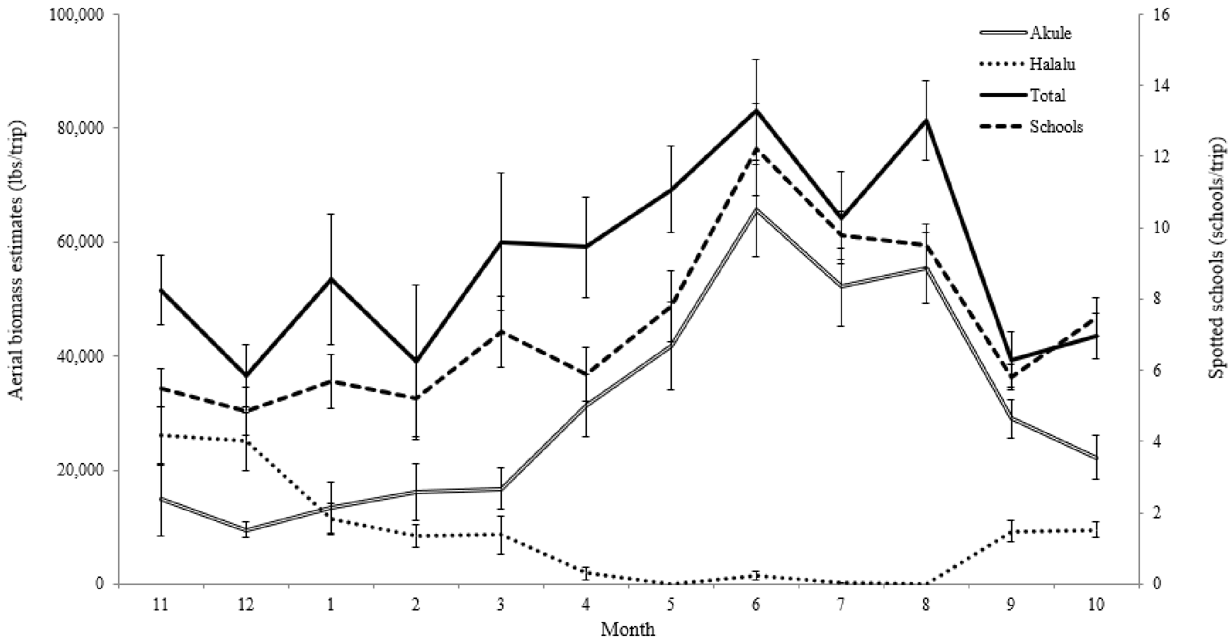

Figure 4. Mean trip biomass for spotted schools of bigeye scad around O'ahu by life stage for adult schools only (akule, double line), juvenile schools only (halalū, dotted line), and combined across life stages including mixed schools (total, black line) on primary axis. Mean number of schools spotted per trip (schools, dashed line) on secondary axis. Error bars represent one standard error from the mean.

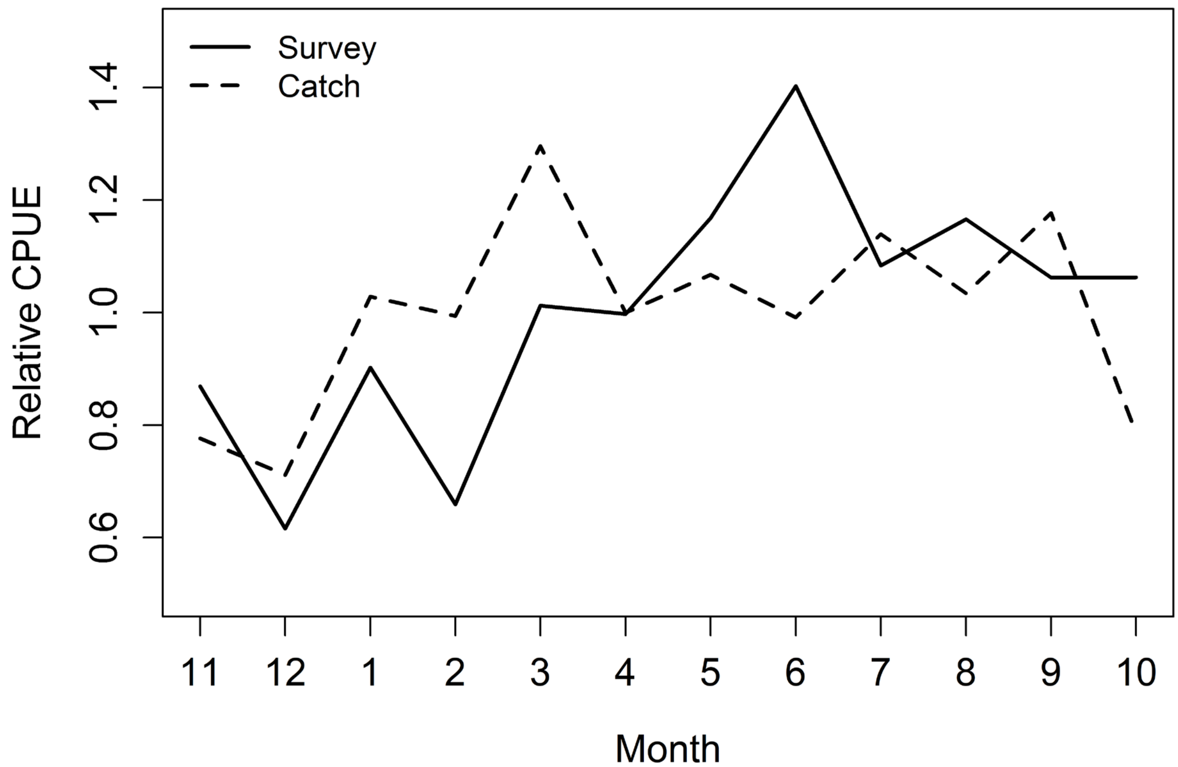

Figure 5: Relative (to the mean) catch per unit effort (CPUE) by month from commercial catch (Catch – dashed line) compared to the relative index of apparent abundance from the fishery-independent aerial survey (Survey – solid line) for the island of O'ahu.

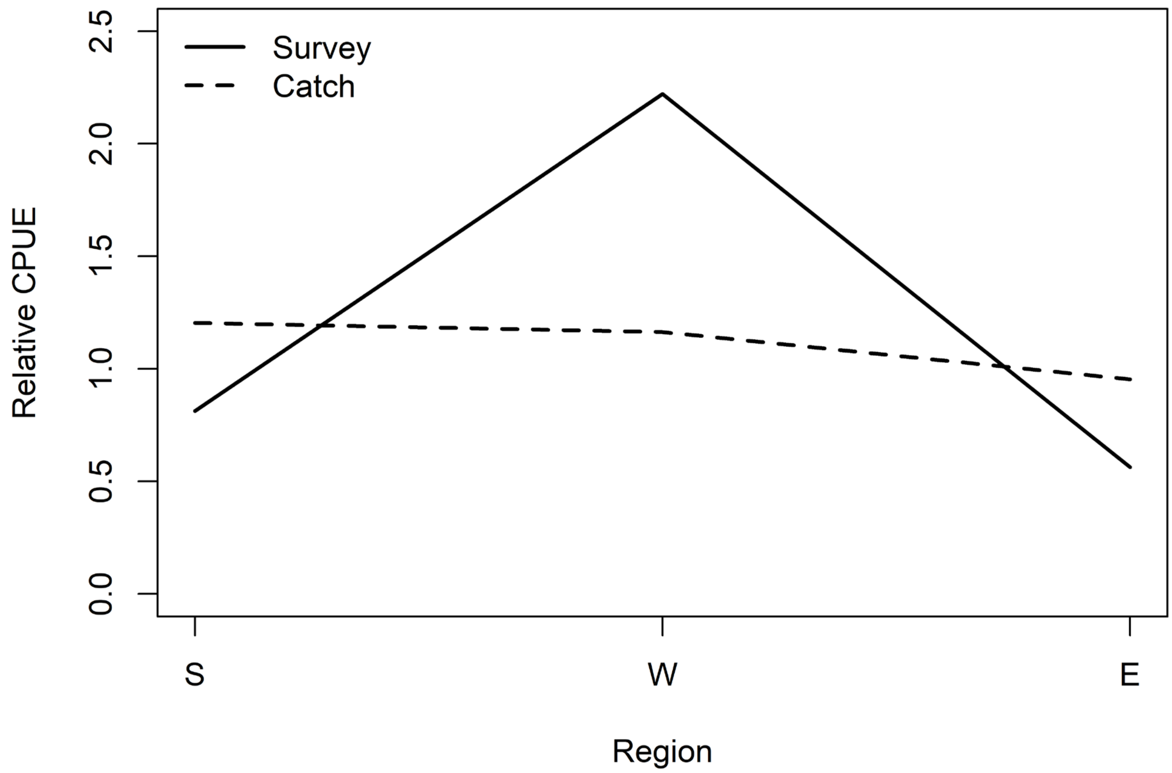

Figure 6: Relative (to the mean) catch per unit effort (CPUE) by region from commercial catch (Catch – dashed line) compared to the relative index of apparent abundance from the fishery-independent aerial survey (Survey – solid line). The northern region is not illustrated due to data confidentiality.