Bringing the right fishermen to the table: indices of overlap between endangered false killer whales and nearshore fisheries in Hawai'i

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ABSTRACT
Incidental bycatch in fisheries is a pressing conservation issue for marine mammal populations across the globe. However, the ability to detect and therefore mitigate this issue is challenging for several reasons. Fishermen are unlikely to voluntarily report bycatch due to fear of penalization or apathy towards it. While fisheries observer programs are sometimes in place to record bycatch, many fisheries have no observers. In Hawaiian waters there are no observer programs in nearshore fisheries, yet interactions with fisheries are likely the greatest threat to the endangered main Hawaiian Islands insular population of false killer whales (*Pseudorca crassidens*). We assess spatiotemporal overlap between false killer whales and nearshore fisheries in Hawaiʻi to identify fisheries and regions where interactions are most likely to occur. Interactions with fisheries was cited as the greatest threat to this population's viability as a result of growing evidence over recent decades. We used false killer whale location data from 38 satellite tag deployments (2007-2018) and commercial fishery catch logs from a corresponding period to develop fishery overlap indices (FOIs) from a perspective that should reflect the experience of local fishermen. The area off Kona has the highest levels of fishing effort, but a low FOI, while high FOI values (up to several thousand times higher than Kona) were found off Oʻahu, Molokaʻi, Maui, Lānaʻi and the north end of Hawaiʻi. Our findings provide direction for where efforts should be focused to effectively monitor and mitigate bycatch for this endangered population of false killer whales.

KEYWORDS: Bycatch; Endangered species; Fisheries; Cetaceans; Pacific

1. Introduction

Developing solutions to marine mammal bycatch in fisheries is challenging at the best of times. In the United States, when bycatch is known to exceed a population's Potential Biological Removal (PBR) level (Wade, 1998), Take Reduction Teams can be formed to bring fishermen, scientists, conservationists and managers together to develop ways to reduce bycatch (Young, 2001). Determining whether bycatch exceeds the PBR level requires information both on population abundance and on bycatch rates, the latter usually obtained through fishery observer programs. When there are no observer programs to determine bycatch rates, as is the case for nearshore fisheries in Hawaiʻi, managing fishery bycatch is much more complicated, in part because some fishermen may be apathetic to incidental bycatch.

There is a small insular population of false killer whales (*Pseudorca crassidens*) found around the main Hawaiian Islands, with an estimated abundance of 167 individuals from mark-recapture analyses of photo-identification data (Bradford et al. 2018). No density estimates are available from line-transect surveys, as there are generally too few sightings attributable to this population available from line-transect surveys (Bradford et al. 2020). Information on the population's range and high-density areas comes primarily from a relatively large data set of satellite-tagged individuals (Baird et al. 2012). Individuals from this population are known to eat a variety of pelagic and reef-associated game fish (Baird, 2016), most of which are the target of commercial and recreational fisheries around the islands. This overlap in diet often leads to false killer whales taking fish from fishermen, and false killer whale depredation of catch has been documented for over 50 years in Hawaiian waters. Pryor (1975) reported false killer whales taking catch off longlines off the Kona coast in 1963, and Shallenberger (1981) noted that depredation behavior “is very common in Hawaii where Pseudorca frequently steal tuna of up to 70 lbs., and sometimes take much larger fish.” Zimmerman (1983) described a group of false killer whales consuming most of an estimated 250 kilogram hooked Pacific blue marlin (*Makaira mazara*) off Kona in 1983. Evidence for more recent fishery interactions has primarily been indirect: individuals from the main Hawaiian Islands (MHI) population have high levels of line injuries on the dorsal fin (Baird et al., 2015) and mouthline (Baird et al., 2017) that are consistent with being hooked in fishing gear. In addition, two of five animals from this population that have stranded since 2010 have had hooks in the stomach, including J hooks typically used in trolling (K.L. West, personal communication). In response to a petition from the Natural Resources Defense Council this population was recognized as a Distinct Population Segment (DPS) under the Endangered Species Act (Oleson et al., 2010) and the DPS was listed as “endangered” in 2012. Interactions with and bycatch in nearshore fisheries is thought to be one of the greatest threats facing this population.

In the case of this population of false killer whales, effectively conveying to fishermen that there may be a bycatch issue has been a slow process for a number of reasons. Most importantly, there are a large number of commercial and recreational fishermen around the main Hawaiian Islands (Pooley, 1993; McCoy et al., 2018), while the false killer whale population is small. The MHI false killer whale population is comprised of at least five social clusters that vary in habitat use (Baird et al., 2012, 2019; Mahaffy et al., 2017), so any one fisherman may only infrequently encounter false killer whales. Compounding this problem are three other similar looking species of “blackfish” (i.e., short-finned pilot whales *Globicephala macrorhynchus*, melon-headed whales *Peponocephala electra*, and pygmy killer whales *Feresa attenuata*) around the islands that are both more abundant than and often confused with false killer whales (Madge 2016; Carretta et al., 2019; Yahn et al., 2019), leading to a common distrust of the false killer whale abundance estimates.

Discussions with fishermen regarding false killer whale bycatch in nearshore fisheries in Hawaiʻi have been occurring in a variety of venues since information emerged that individuals from the main Hawaiian Islands population have relatively high levels of fishery-related injuries (Baird and Gorgone, 2005; Baird et al., 2015, 2017). These discussions have included annual meetings of the Pacific Scientific Review Group — an advisory body to NOAA Fisheries; various meetings of the Western Pacific Regional Fishery Management Council and its advisory bodies; a recovery-planning workshop held by NOAA Fisheries in Honolulu in October 2016; and the annual meeting of the Marine Mammal Commission in Kona in May 2019. Fishermen at these meetings have often commented that they’ve never had interactions with false killer whales and expressed their belief that depredation by or bycatch of false killer whales in nearshore fisheries in Hawaiʻi rarely, if ever, occurs. However, depredation by false killer whales is occasionally self-reported by fishermen as part of the reporting required for commercial license holders (Boggs et al. 2015) or in anonymous interview surveys (Madge 2016).

The purpose of this study is to understand how endangered false killer whales overlap and potentially interact with nearshore fisheries around the main Hawaiian Islands, in the absence of observer data in these fisheries. To examine overlap and assess where interactions with fisheries are most likely to occur, we characterize the spatial distribution of both false killer whale satellite tag data (Baird et al., 2012) and nearshore commercial fisheries using data from the state's Commercial Marine Licensing (CML) reporting system. Fishermen who sell their catch in Hawai'i or run fishing charter services are required to have a CML. CMLs are not specific to fisheries or fishery methods, and CML holders can fish multiple gear types. CML holders only declare fishing methods when reporting catch and effort by commercial fisheries statistical areas. While it is possible for there to be several CML license holders on a single fishing vessel, the CML database used in this study does not provide such information. We use data from these fishing reports for 2007 through 2017, a period that overlaps with almost all of the satellite tag data available for the main Hawaiian Islands insular population of false killer whales (2007-2018). We then combine these two data streams to identify areas where individual fishermen are most likely to interact with false killer whales. In particular, we develop fishery overlap indices to assess the relative probability of an individual fisherman having false killer whales in their area when fishing. Such indices should allow for identifying which fishermen likely have the highest interaction rates, and thus may be the most qualified for assisting in the development of solutions to the depredation and bycatch issue. This research is meant to contribute to ongoing efforts to create a recovery plan and implement recovery actions for this endangered population.

2. Methods

CML fisheries statistical areas include narrow strips extending approximately 3-4 km offshore along each of the main Hawaiian Islands, contiguous blocks that extend the nearshore strips offshore approximately 30-35 km, and a grid system of blocks approximately 35-38 km per side in pelagic areas around the islands (Fig. 1). We used these fisheries reporting areas for comparisons of satellite tag and fisheries effort data.

2.1. Tag data analyses

Methods related to the false killer whale satellite tagging data set have been published in detail (Baird et al., 2010, 2012) and so are only briefly summarized here. A total of 52 tags were deployed from 2007 through 2018, including Wildlife Computers SPOT5 (n=34) and SPOT6 (n=13) location-only tags as well as a small number of SPLASH10 location-dive tags (n=5). Location data were first processed by Argos using a least-squares method, and subsequently filtered for unrealistic locations with a Douglas Argos-filter using a distance-angle-rate filter (Douglas et al., 2012), with user defined parameters as noted in Baird et al. (2012). We assessed potential coordination of individuals by measuring the straight-line distances between all pairs of individuals when locations were received during the same satellite overpass. Individuals were considered to be acting in concert when mean distances between a pair were less than 5 km and maximum distances were less than 25 km. In such cases we used only one from each pair (the longest duration track) in analyses.

We quantified false killer whale spatial use by calculating total visit duration (i.e., total amount of time spent) in each fisheries area as a proxy for density, following Baird et al. (2012). Total visit duration was calculated by using a spatial join to associate positions for each fisheries area. Tracks were made by connecting positions in temporal sequence and intersecting tracks within each fisheries statistical area. This assumes that the animal was traveling at a constant speed between consecutive points. The time spent in each area was calculated by multiplying the travel speed of the animal during each segment by the straight line distance that was inside each area. Because the interpretation of total visit duration may vary by area size, we calculated density by dividing total visit duration by the size of each fisheries statistical area, which vary in size from 56 to 2,449 km^2 (median=1,007 km^2).

$$\text{Total visit duration per unit area} = \frac{False\ killer\ whale\ cumulative\ time\ in\ fisheries\ area\ (days)}{size\ of\ fisheries\ area\ (km^2)}$$

In addition, we applied a "late start," where we excluded an initial period of time post-tagging for each individual to reduce any potential bias related to the island off which the animal was tagged. To do this we calculated the time needed to travel to the farthest point of the known range of the population and removed records from that period of time. This calculation was based on where the animal was tagged and the average travel speed for that individual. Calculated periods of time excluded ranged from 2.5 to 9.7 days (median=4.7 days), representing from 3.6% to 53.4% (median=9.6%) of each tag record. Plots of false killer whale density by fisheries area are presented as standard deviations above or below the mean value. We interpret values from 1 to 2 SDs above the mean as high density areas, and values of >2 SDs above the mean as very high-density areas. We assessed variability in whale density per fisheries area by Hawaiʻi oceanographic seasons, which are based on average sea surface temperatures (Flament, 1996): winter—February-April; spring—May-July; summer—August-October; fall—November-January, and social cluster (Clusters 1 through 5). All analyses were conducted in R version 3.6.0 (R Core Team, 2019).

2.2. Fisheries data analyses

CML catch and effort data were obtained from the Hawaiʻi Department of Land and Natural Resources Division of Aquatic Resources (DAR).. To address confidentiality concerns, data were summarized for all presentations such that there were no less than three licensees reporting landings in any data strata, or the number of licenses were intentionally obscured by presenting summarized data products as standard deviations above or below the mean. We restricted analyses of CML data to years that overlapped with false killer whale satellite tag data (2007 through 2017). Although there were satellite tag data available for February and March 2018, CML data were not available for the entire year at the time of these analyses, thus partial fishery effort data for 2018 were excluded. Catch data for each gear type/fishery were examined to determine primary catch species (defined as those making up >10% of the total catch by weight). Fisheries included in the analyses were those where one or more of the primary catch species were known to be part of the diet of the MHI insular false killer whale population (Table S1). Fisheries considered in the analyses (as defined in the CML reporting database) were aku boat, deep-sea handline, hybrid (troll/handline/other), ika-shibi, kaka line, palu-ahi, rod & reel/cast/jig, short line, troll, troll bait, troll lure, troll stick, vertical longline, and "other" (Table 1). A number of other gear types (e.g., inshore handline) did catch species that are false killer whale prey but those species were not primary catch species, and thus these fisheries were excluded from analyses.

Fishing effort was assessed using several metrics, including total number of vessels, total number of days of fishing effort, and total catch, both within each fisheries statistical area and summarized over the entire study area. The total number of vessels was computed as the sum of unique fishing licenses reporting catch in any fisheries statistical area over the 11-year period of interest. Total number of days of fishing effort was calculated as the sum of days fished by each unique license. Total catch was calculated as the sum of kilograms of fish caught over the entire period of interest. Fishing effort metrics were adjusted for the size of each fishing area by dividing the effort metric by the fishing area size. We assessed correlation among all three metrics of fishing effort by computing one-tailed Pearson correlation coefficients. To provide a common basis for visualization of different fishing effort density measures, we plotted each measure as standard deviations above or below the mean value. Following the analyses for whale density, we interpret values from 1 to 2 SDs above the mean as high density areas, and values of >2 SDs above the mean as very high-density areas. We assessed variability in fishing effort over several temporal scales (annual, seasonal, monthly).

2.3. Fisheries overlap indices

The goal of the indices is to represent the perspective of fishermen in a way that reflects the probability of interactions with false killer whales. For example, if there is a single vessel fishing in an area with several false killer whales, the probability of a whale overlapping in space and time when the vessel hooks a fish would be relatively high. If there were many vessels fishing in an area and only a single whale, from the perspective of thefishermen the probability of overlapping at a time when the vessel hooked a fish would be relatively low. These indices presuppose that there is some probability that false killer whales will actively approach fishing vessels or attempt to depredate catch if they are nearby when a fish is hooked.

We calculated fishery overlap indices (FOI) using both false killer whale total visit duration per area and fishing effort. As fisheries log data were only used through 2017, we assume fishery efforts in 2018 were similar to those across the entire study period, which was supported by preliminary analyses. To provide a basis for comparison among areas with a reference value that could be broadly relevant to fishing communities in Hawai‘i, we scaled the FOIs in reference to values for Kona (area 121; Fig. 1). This area had the largest catch (17.7% of all fish caught by weight), number of licenses (a combined 1,228 over the 11-year period), and days fished (a combined 59,442 over the 11-year period) of any of the fisheries statistical areas (Table S2). This area also receives a lot of attention throughout Hawai‘i as the premiere location for fishing tournaments, and thus fishermen throughout the state may be able to relate to this area when making comparisons with other areas where only a smaller number of fishermen have experience. As all three measures of effort were correlated (see supplemental materials), we focused on calculating a FOI based on the number of days fished, as this should prove the most direct measure of potential interactions. The Kona FOI was calculated as:

$$\text{Kona FOI} = \frac{Total\ visit\ duration\ per\ unit\ area\ in\ area\ 121}{number\ of\ days\ fished\ \ in\ area\ 121}$$

The scaled FOIs for each area were thus calculated as:

$$\text{FOI} = \frac{Total\ visit\ duration\ per\ unit\ area}{number\ of\ days\ fished\ in\ area} * \frac{1}{Kona\ FOI}$$

Thus, the scaled FOI value for Kona (area 121) was 1, and all other areas were calculated relative to this. For visual comparisons index values were graphically represented relative to Kona in bins (e.g., < 5 times, 5 – 10 times, 10 – 50 times, 50 – 200 times, etc).

3. Results

3.1. False killer whale spatial use

After restrictions for pseudoreplication (i.e., removing one individual per pair of tagged individuals acting in concert), data from 38 satellite tag deployments from 2007 through 2018 were used in false killer whale density analyses. After late start analyses (i.e., removing the initial period of each deployment), individual tracking data used ranged from periods of 6.1 to 189.0 days (median=45.0 days), for a cumulative total of 2,205.7 days. Location data were obtained from all years over the 12-year span, although with substantial gaps throughout that period (Fig. S1). Tags used in analyses were deployed off Kaua‘i (n=1), O‘ahu (n=13), Lāna‘i (n=2), Maui (n=2), and Hawai‘i (n=20), and were deployed on individuals from all five social clusters (Cluster 1, n=22; Cluster 2, n=3; Cluster 3, n=5; Cluster 4, n=3; Cluster 5, n=5). For Cluster 1, the 22 deployments involved 20 individuals, with two individuals each tagged twice (one individual tagged in 2008 off Hawai‘i and 2009 off O‘ahu (see Fig. 3A & 3B in Baird et al. 2012), and one tagged in 2008 off Hawai‘i and in 2016 off O‘ahu). A comparison of movement patterns for each pair of deployments (not shown) indicated the individuals had very different spatial use patterns for each of their two deployments, and thus both deployments for each pair were used in analyses. While there were tag location data from throughout the year, there were strong seasonal biases by cluster (Fig. S1).

Plots of total visit duration revealed high or very high use primarily in offshore areas (Fig. 2). Low density areas (from -1 to 1 SDs around the mean value) were found off Kaua‘i, Ni‘ihau, and the southern half of Hawai‘i. Very high-density areas (defined as >2 SD above the mean) varied by cluster, but included areas off eastern O‘ahu, Penguin Bank, south and east of Lāna‘i, north of Moloka‘i and Maui, and off the north end of Hawai‘i (Fig. S2). Very high-density areas also varied seasonally (Fig. S3), with fall (November – January) and winter (February – April) having highest density areas off eastern O‘ahu and Moloka‘i, a broadening of high density areas in spring (May – July) from eastern O‘ahu to northern Hawai‘i, and with highest density areas concentrated off northern Hawai‘i in summer (August – October). Because of the potential interaction between social cluster and season (Fig. S1), we also examined seasonality using information only from Cluster 1, the group with the largest number of tag deployments (n=22; Fig.S4). Seasonal patterns for Cluster 1 were broadly similar to the overall pattern (e.g., a shift from Hawai‘i to Molok‘i from summer to fll; Fig. S3, S4), but also showed some patterns that were obscured when examining the larger data set (e.g., high-density areas off nearshore Kona and Hāmākua in spring).

3.2. Variability in fisheries effort

Data from 14 fisheries as noted in the CML database were included in analyses of fishing effort (Table 1) based on overlap of primary catch species with false killer whale diet (Table S1). Of the 125 commercial fisheries statistical areas with overlap by false killer whale satellite tag track lines (Fig. 1), 117 had fishing effort during the 2007-2017 period. Three of the 117 were excluded for confidentiality reasons as they had less than three licenses, and 24 additional areas were excluded as they had less than an average of one day per month of fishing effort, resulting in calculation of fishery effort statistics for 90 areas. With the exception of area 307, an area along the north side of Kaho‘olawe where fishing is generally restricted, and area 312, along the

NW coast of Moloka‘i, all excluded areas were in offshore areas. It should be noted that the offshore areas that were excluded generally had very low levels of false killer whale use (Fig. 2).

The troll lure fishery was by far the largest fishery based on number of licenses, total days fished, and weight of primary catch species caught (Table 1). All three measures of fishing effort (i.e., catch, number of days fished, number of licenses) were highly correlated (correlation coefficients 0.84 to 0.95). Regardless of the measure of fishing effort used (Table S2), or density of those measures (i.e., effort divided by area size; Fig. 3), there was broad similarity among the islands in terms of relative fishing effort. Based on density (effort per unit area), a number of areas had high or very high levels of fishing effort with one or more metrics (Fig. 3): eastern Kaua‘i (nearshore), Wai‘anae and the south and northeast shore of O‘ahu (nearshore and offshore), Kona (nearshore and offshore), south Kohala (nearshore), South Point (nearshore), Puna (nearshore), and Hilo (nearshore and offshore). Fishing effort did vary slightly over the 11-year period, with a gradual increase in the number of licenses and number of days fished up until 2012, and a slow decrease from 2013 through 2017 (Fig. S5). Fishing effort peaked in May through July (Fig. S5). Spatial distribution of fishing effort also varied seasonally, with the greatest changes in total catch (Fig. S6). The majority of individual license holders that fished an average of at least one day per month over the study period fished with more than one fishing method (Fig. S7).

3.3 Fishery overlap indices

Fishery overlap indices were calculated for 90 areas (Fig. 4, Fig. S8). These 90 areas accounted for 95.4% of all of the false killer whale time from satellite tag data analyses. In the excluded areas (i.e., those with fewer than three licenses or an average of one day of fishing effort per month), the percentage of time spent by false killer whales ranged from 0.001% to 0.748% (median=0.036%). For the 90 focal areas, the percentage of time spent by tagged false killer whales ranged from 0.007% to 14.89% (median=0.17%). There were 62 areas where false killer whales spent less than half of one percent of their time, and five areas where they spent more than five percent of their time (a combined 44.8% of their time). None of these five areas were in the top 10 areas for kilograms of fish caught, although one of them (area 122, N Kona offshore, see Fig. 1) ranked fifth for number of days fished and fourth for number of licenses (Table S2).

Of the 90 areas for which FOIs were calculated, FOI values for Kona (area 121) were ranked the 4th lowest using days fished (Table 2). Compared to values off area 121 there were relatively low FOI values offshore around Kaua‘i and off the southern half of Hawai‘i (nearshore and offshore), intermediate to high FOI values off parts of Ni‘ihau, O‘ahu, Maui and Lāna‘i, and very high FOI values off Moloka‘i, the east and north side of O‘ahu, in some nearshore areas off Maui, and off the north end of Hawai‘i (Fig. 4; Table 2, S4). There were broad similarities in the locations of the highest FOI areas when comparing relative values to values represented as SDs in relation to the mean value (Fig. 4, S7). Predominant fishing methods varied among the areas with high FOI values (Table S4).

4. Discussion

In the absence of observer data, assessing where interactions between marine mammals and fisheries are most likely to occur is difficult, to say the least. There is a natural tendency to assume that the areas with the greatest amounts of fishing effort may be the areas with the highest probability of interactions occurring, but from the perspective of the fishermen, this may not be the case. Our development of fishery overlap indices to reflect the relative probability of overlap between false killer whales and individual commercial fishermen showed that the area off Kona (area 121) is one of the areas in the main Hawaiian Islands where a fisherman may be least likely to experience false killer whale depredation of his catch. While Kona is the area with the highest fishing effort, regardless of which measure of fishing effort was used (total catch, days fished, or the number of licenses), Kona was in the bottom 10% of the 90 areas for which FOIs were calculated. This finding has important implications for discussions going forward with fishermen on how to address both depredation by and potential bycatch of false killer whales in nearshore fisheries. Despite the fact that Kona is responsible for the greatest levels of catch, licenses, and days fished (Table S2), fishermen off Kona likely have little experience with depredation or false killer whale bycatch, particularly in comparison to areas with high FOIs. From the perspective of identifying fishermen that may have the most frequent interactions with false killer whales, those that fish off the north and east side of O‘ahu, Moloka‘i, the north side of Maui, and the north end of Hawai‘i are all likely to have a much higher probability of interacting with false killer whales compared to those that fish in areas off the southern half of Hawai‘i or off Kaua‘i (Fig. 4). The highest FOI values are up to several thousand times higher than that off Kona (Table 2).

Our findings have important implications for how to address depredation and bycatch of false killer whales in nearshore fisheries in Hawai‘i. Identification of areas where fishermen are most likely to have interactions with false killer whales is particularly relevant to managers when deciding where to expend their mitigation efforts. A study by Madge (2016) involving interviews of fishermen in Hawai‘i found that many had difficulty discriminating among species of “blackfish.” Fishermen that regularly fish in areas with high FOI values could be the focus for targeted outreach efforts to aid in improving identification skills and generally raising awareness of the behavior of different species, particularly as it relates to the likelihood of depredation of catch. For example, melon-headed whales and short-finned pilot whales, two other similar looking species, feed primarily at night and deep in the water column on squid or small fish (West et al., 2018; Owen et al., 2019) that are unlikely to overlap with the catch of most nearshore fisheries. Knowing that these species are unlikely to depredate catch may benefit fishermen, who sometimes may pull gear or move to a different area if they think there is a high likelihood of depredation from whales nearby. Being able to recognize false killer whales, and the potential risk of associated depredation, similarly means that any actions fishermen may take (e.g., pulling gear and moving) may be warranted, rather than unnecessary. Outreach efforts may be most effective targeted at ports of departure or landing that are primarily used for access to high FOI areas, or through contacting license holders that fish regularly in the areas through mailings or by phone, rather than on-water interceptions. There are a limited number of harbors or launch ramps for most of the main Hawaiian Islands (e.g., there are only two each on Lāna‘i and Moloka‘i), and license holders declare ports of departure and landing, so determining which license holders use high FOI areas should be relatively straight-forward.

Our results also suggest that measures to gather additional information on interactions between fishermen and false killer whales, such as observer efforts or electronic monitoring, should be focused on fishing that occurs within these high FOI areas. Given the large number of fishermen with CMLs in Hawai‘i (typically 2-3,000 per year) and the small number of false killer whales in the population, any sort of observer program or electronic monitoring would require a substantial investment if applied uniformly across the fishing fleet. As noted however, fishermen in some areas (e.g., offshore of Kaua‘i or the southern half of Hawai‘i) likely have very low interaction rates in comparison to those fishing in areas such as off Moloka‘i, eastern O‘ahu or Kohala. Selectively targeting such areas for monitoring would reduce costs and increase the likelihood of obtaining a useful sample size of interactions. Considering all fishing methods, trolling of one sort or another (i.e., with lure, bait, or stick) represents the majority of effort, regardless of which measure of effort is used (Table 1). However, the predominant fishing methods used in some of the high FOI areas often differs (Table S4). For example, rod and reel, cast/jig fishing is the predominant method in the three of the top 30 FOI areas, yet represents a small proportion of the total catch over all fishery methods (Table 1). Individual license holders also may use multiple fishing methods or gear types, and the majority of “active” fishers (i.e., those that fished an average of at least one day per month over the study) used more than one fishing method (Fig. S8). Regardless of the specifics, this suggests that finding the right fishermen to engage in developing bycatch mitigation measures will require working with fishermen that collectively use a wide variety of fishing methods. In addition to outreach efforts, studies on the human dimensions of fishermen-false killer whale interactions would be valuable in the development of cooperative and effective bycatch mitigation efforts. These could include studies of perspectives, attitudes, understanding, and values towards interactions, and would provide a more informed understanding of the issue from the perspective of the fishermen, as well as aid in developing trust between fishermen and management agencies (Ford et al. 2020).

Our analyses assume that our 38 tagged individuals are broadly representative of the population. False killer whales do forage in relatively large groups of related individuals, and individuals have strong and enduring bonds (Baird et al. 2008; Baird 2016; Martien et al. 2019), suggesting that the tagged individuals do represent the spatial use of groups of individuals. Our analyses to address pseudoreplication, i.e., the removal of 14 tagged individuals from the sample as they were traveling in concert with others, supports this suggestion. However, more than half the tag deployments we used came from one social cluster, and spatial use does vary by cluster (Fig. S2), as well as seasonally (Fig. S3), suggesting that additional data from the less-sampled clusters and filling more seasonal gaps would be of particular value. We also assume that each deployment represents a similar number of individuals within the population, for example, that a deployment on a Cluster 1 individual represents the same number of individuals as a deployment on a Cluster 2 individual. While we know that cluster size varies (Bradford et al. 2018), there are no current estimates of the size of the five social clusters, as two of them were only recognized subsequent to the Bradford et al. (2018) abundance analyses (Baird et al. 2019). Thus, we are unable to assess exactly how this assumption influences our conclusions. This could be addressed in part by examining cases when more than one tag is deployed on a social cluster at one time, to see if there are differences in inter-animal distances among clusters, but such analysis is beyond the scope of this study.

Our analyses also assume that the probability of a false killer whale depredating catch when near a fishing vessel with a fish on the line is equally likely whether they are in an area with high or low levels of fishing effort, i.e., that they do not switch from normal foraging behavior to depredation only when there are many opportunities for depredation. Observations from extended encounters from our field efforts (Baird et al. 2008, 2013) are relevant, since we have over 40 encounters from the top four fishing areas, in terms of number of licenses (Table S2). Despite having many fishing vessels in the area during these encounters, we have never witnessed false killer whales approaching fishing vessels that are actively bringing in catch, or milling around a fishing vessel (Baird, unpublished).

There are also a number of other limitations or potential biases with our fishery overlap indices. These include: fishing methods that were excluded from our analyses; potential heterogenous false killer whale (or fishery) spatial use of the larger offshore fishing statistical areas; bias associated with islands where individuals were tagged; and the restriction of our analyses to commercial fishing effort. False killer whales in Hawaiʻi have a diverse diet that includes both pelagic and reef-associated game fish (Baird 2016; Table S1), and fishing methods included in the analyses were those that had pelagic game fish as the primary catch species. Many other fishing methods in Hawaiʻi catch both pelagic and reef-associated game fish that are known to be part of the diet of this population of false killer whales, but these species were not the primary species caught. In addition, recreational fishing effort in Hawaiʻi is likely responsible for a much greater total catch than commercial fisheries, particularly of reef-associated fish (McCoy et al., 2018), but the lack of comprehensive recreational fishing statistics (i.e., effort metrics by area) limits the ability to assess how recreational fishing effort might influence such indices. We attempted to address tagging site (i.e., island) bias by removing the initial portion of each tag deployment period equivalent to the amount of time needed for that tagged individual to travel to the periphery of the population range. That said, there is a possibility the low FOI values off Kauaʻi reflect in part the small number of individuals used in the analyses that were tagged off that island, although the only social cluster that has been documented off Kauaʻi is Cluster 1, with the largest sample size of tag deployments. Ironically, for the one tagged individual from Kauaʻi, the animal had moved away from Kauaʻi during that initial period of time where data were excluded, reducing the amount of time false killer whales spent around Kauaʻi in the analyses. Regardless, additional tag deployments in the central (Oʻahu) and western (Kauaʻi) part of the range of this population would be of value for addressing this potential bias. Lastly, while the nearshore fisheries statistical areas were relatively small (~100-250 km^2), the contiguous offshore areas are much larger (~500-2,500 km^2). Both large and small areas were ranked high in terms of FOIs (Table 2, Fig. 4). However, our indices implicitly assume that false killer whales use these areas randomly or uniformly, when in fact satellite tag data examined on a small spatial scale show higher densities in some areas (Baird et al., 2012), and spatial patterns may vary due to a wide range of environmental factors (Baird et al., 2019). Given the spatial resolution of the fishery effort data we are unable to address this potential bias, but it could have some influence on the probabilities of overlap between false killer whales and individual fishermen.

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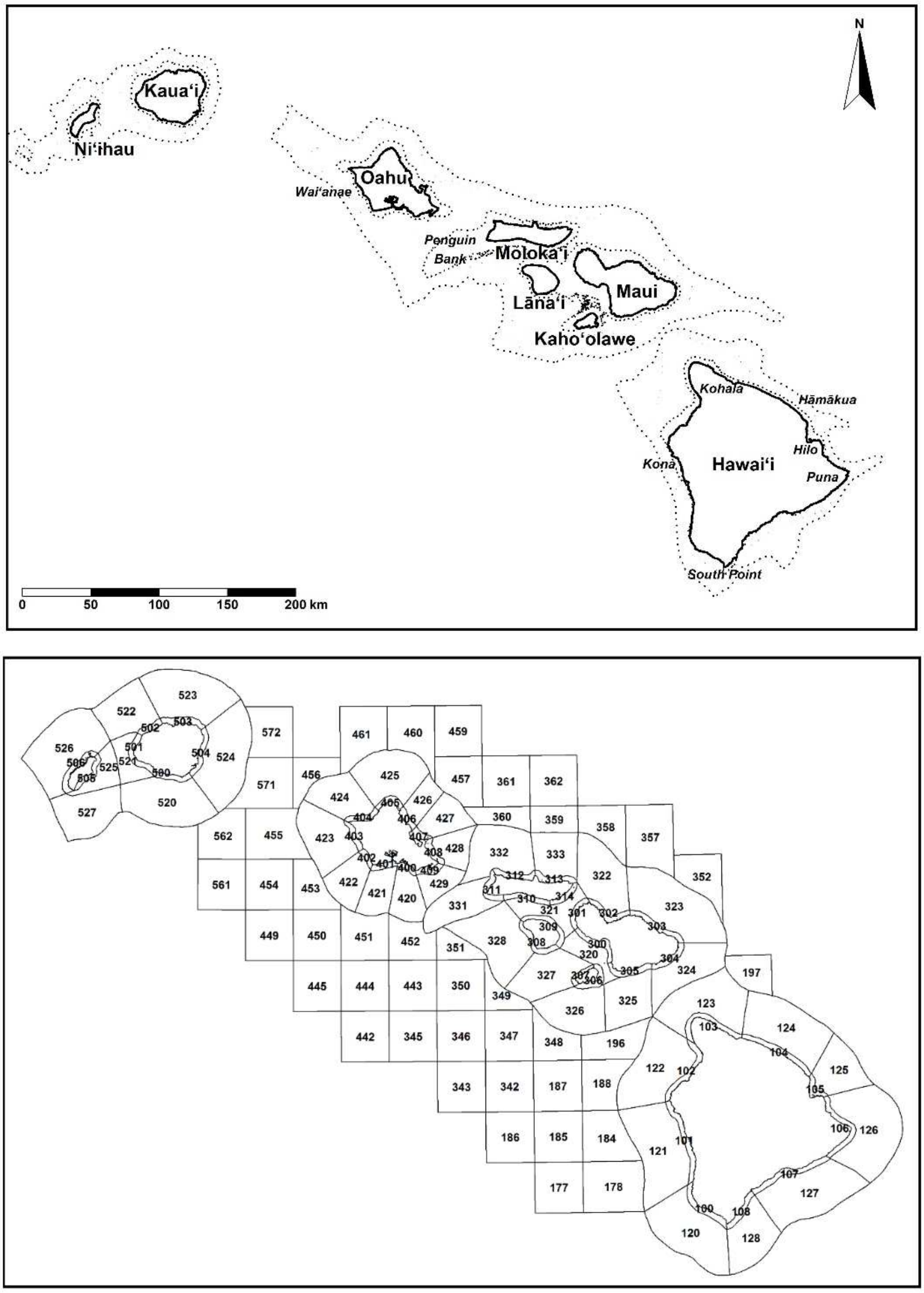


Fig. 1. Top. The main Hawaiian Islands with place names noted in text, showing the 200 m and 2000 m isobaths. Bottom. Commercial fisheries statistical areas used for the Hawai'i Commercial Marine License reporting system. Only those areas where satellite-tagged individuals from the main Hawaiian Islands insular false killer whale population have been recorded or have passed over on interpolated tracks from satellite tag locations are shown.

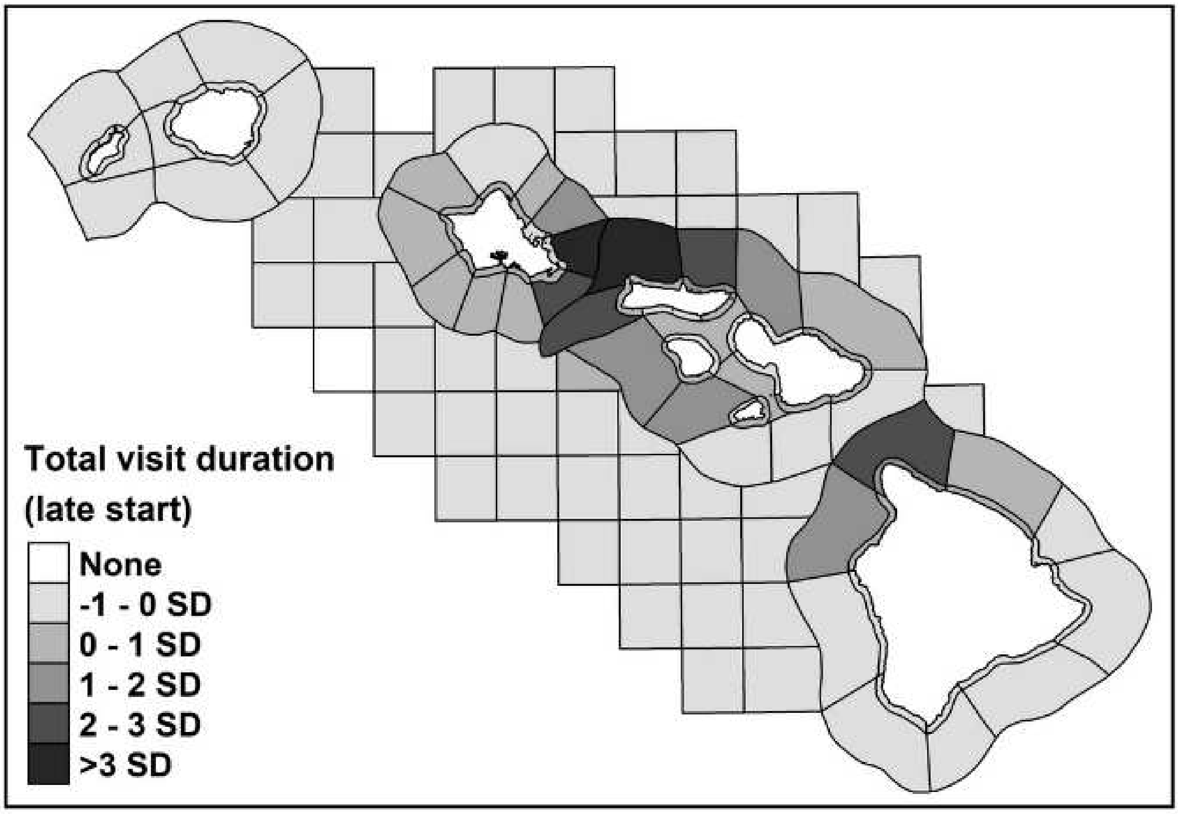


Fig. 2. False killer whale (n=38) spatial distribution among the Hawai'i commercial fisheries statistical areas 2007-2018, represented as total visit duration adjusted with a "late start" to account for potential bias associated with the island the animal was tagged at. Total visit duration was adjusted for the size of each area (km^2) and shades represent standard deviations above or below the mean value. All social clusters were pooled.

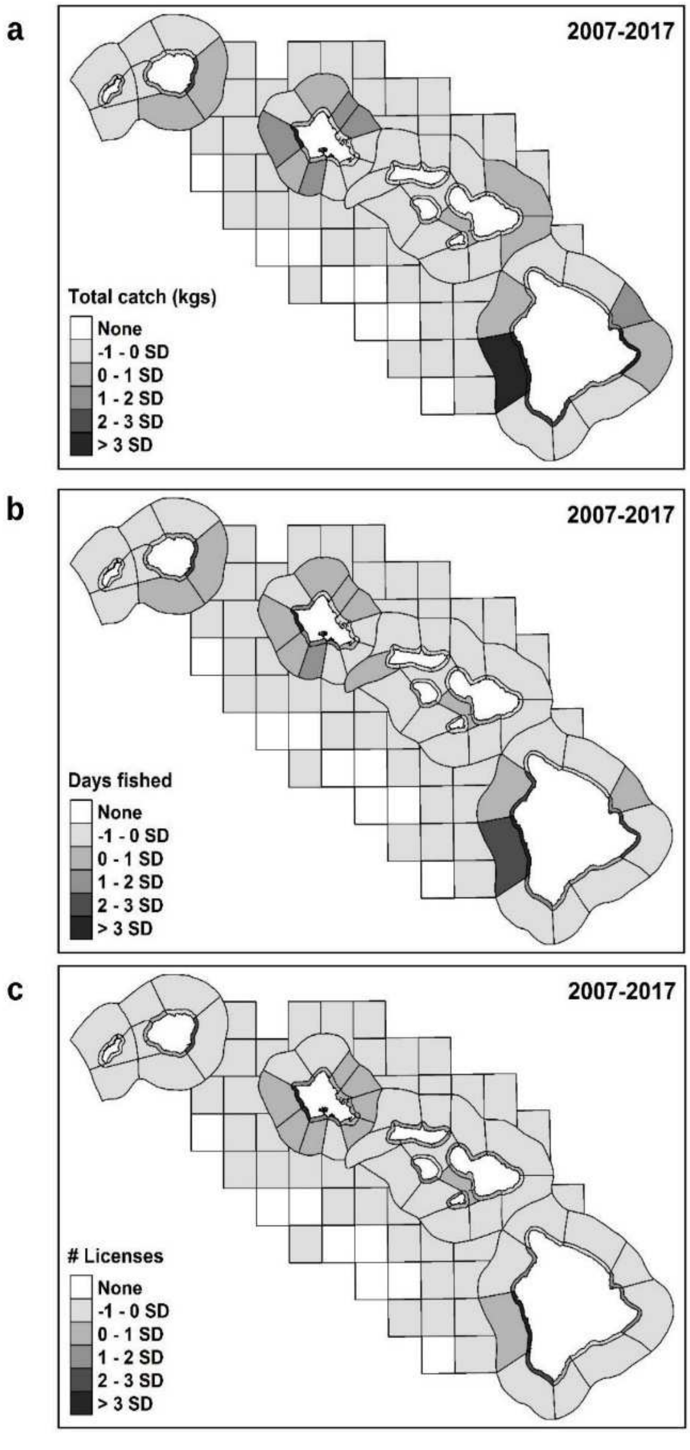


Fig. 3. Spatial distribution of fishing effort density (effort corrected for area size (km^2)) across Hawai‘i commercial fisheries statistical areas. Fisheries were restricted to those listed in Table S1, for the time period (2007-2017). (a) Total catch. (b) Number of days fished. (c) Number of commercial marine licenses. (Shading represents standard deviations above or below the mean value for each measure.

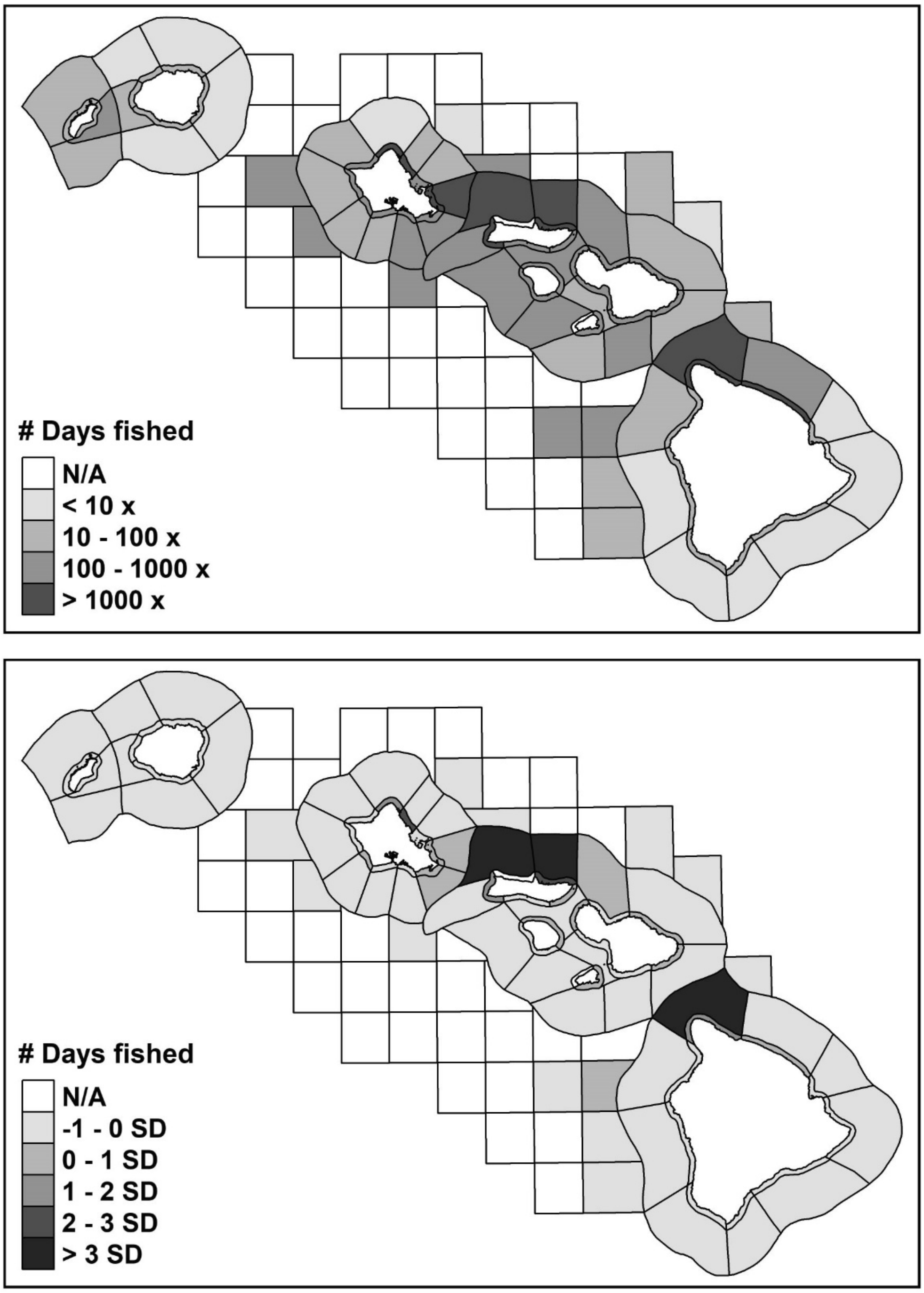


Fig. 4. Fishery overlap indices using the Hawai‘i commercial fisheries statistical areas. Top. FOI with values shown relative to Kona offshore (area 121). Bottom. Distribution of FOI values represented as SD above or below the mean value. Areas with fewer than three licenses or with less an average of one day of fishing effort per month area are shown as N/A. Fishery areas shown are all those with overlap from satellite-tagged false killer whales from the main Hawaiian Islands population.

Table 1. Fisheries considered in analyses of fishery effort based on primary fish species caught. Measurements of effort span 2007 – 2017. List ranked based on catch of primary species in decreasing order.

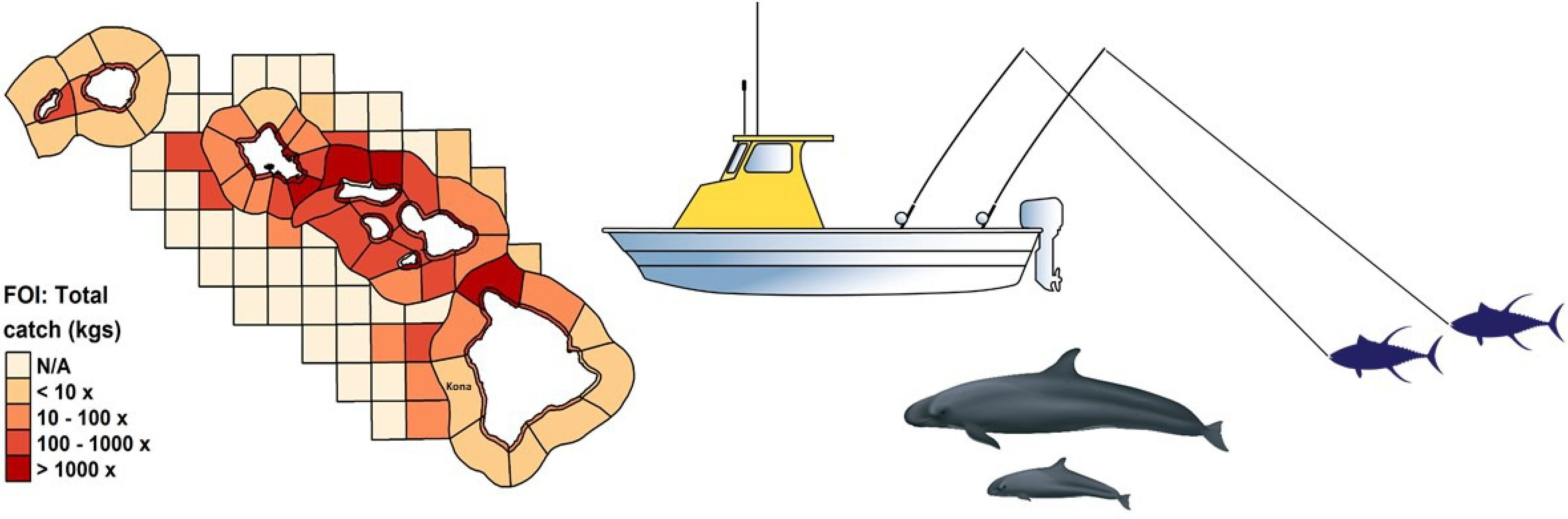
Fishery	**# licenses**	**Total days fished**	**% of days fished**	**Total kilograms primary catch species**	**Primary catch species[1] (>10% by weight) in decreasing order**
troll lure	3,945	207,831	73.0	9,830,102	ahi, mahimahi, ono, a‘u
palu ahi	963	25,638	9.0	2,567,336	ahi, ‘ahi po‘onui
ika-shibi	725	15,362	5.4	2,439,400	ahi, tombo ahi, ‘ahi po‘onui
hybrid	28	2,308	0.8	1,866,108	‘ahi po‘onui, ahi
troll bait	1,522	2,705	1.0	1,836,192	mahimahi, ahi
aku boat	8	718	0.3	1,157,469	aku
short line	46	2,383	0.8	754,074	‘ahi po‘onui, ahi
troll stick	181	1,894	0.7	336,417	ahi, ‘ahi po‘onui
deep-sea handline	1,030	13,297	4.7	265,946	monchong, ahi, kāhala
rod & reel/cast/jig	938	11,646	4.1	136,580	ahi, mahimahi
vertical longline	43	200	0.1	27,387	‘ahi po‘onui, monchong, ahi
troll	72	254	0.1	22,371	ahi, mahimahi, ono
other	64	117	0.0	7,486	‘ahi po‘onui, ahi
kaka line	51	197	0.1	7,458	monchong

[1]See Table S1 for English and scientific names of fish species

Table 2. Fishery overlap indices (FOI) for the 30 commercial fisheries statistical areas with the highest FOI values (sorted in decreasing order), scaled to the value off Kona (area 121; FOI = 1). See Fig. 1 for area locations.

Area #	**Description**	**Area size km²**	**FKW % of time in cell**	**Fishery overlap index**
332	Moloka‘i NW offshore	1,615	15.88	5,227
333	Moloka‘i NE offshore	1,013	4.40	4,192
123	Kohala offshore	1,926	10.59	4,099
313	Moloka‘i NE nearshore	127	0.43	2,840
406	O‘ahu NE nearshore	76	0.12	2,482
311	Penguin Bank nearshore	125	0.22	1,722
103	Kohala nearshore	212	0.82	1,630
405	O‘ahu N nearshore	95	0.16	1,425
408	O‘ahu E nearshore	95	0.09	1,329
428	O‘ahu E offshore	644	5.00	1,209
104	Hāmākua nearshore	215	0.39	1,208
314	Moloka‘i SE nearshore	97	0.11	884
304	Maui SE nearshore	122	0.17	780
306	Kaho‘olawe E nearshore	134	0.15	770
409	O‘ahu SE nearshore	98	0.20	769
429	O‘ahu SE offshore	563	2.78	734
303	Maui NE nearshore	174	0.30	694
309	Lāna‘i E nearshore	155	0.12	693
301	Maui W nearshore	96	0.08	612
188	S. Kohala far offshore	1,065	0.40	582
322	Maui NW offshore	1,577	6.08	577
402	Wai‘anae S nearshore	56	0.13	550
360	Moloka‘i NW far offshore	627	0.18	466
455	Wai‘anae N far offshore	1,504	0.57	446
400	Honolulu nearshore	60	0.10	433
407	Kāne‘ohe nearshore	104	0.09	429
124	Hāmākua offshore	2,057	2.01	396
302	Maui NW nearshore	142	0.10	367
453	Wai‘anae S far offshore	888	0.20	354
305	Maui S nearshore	143	0.18	252

Fishery overlap indices between endangered main Hawaiian Islands false killer whales and commercial fishing effort in Hawai‘i



$$\text{Kona FOI} = \frac{Total\ false\ killer\ whale\ visit\ duration\ per\ unit\ area\ in\ Kona}{fishing\ effort\ (catch, days\ fished, licenses) in\ Kona}$$

$$\text{FOI} = \frac{Total\ false\ killer\ whale\ visit\ duration\ per\ unit\ area}{fishing\ effort\ (catch, days\ fished, licenses) in\ area} * \frac{1}{Kona\ FOI}$$