Field studies and analyses from 2020 through 2022 to support the cooperative conservation and long-term management of main Hawaiian Islands insular false killer whales

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Executive summary

In 2012 the main Hawaiian Islands (MHI) insular population of false killer whales (*Pseudorca crassidens*) was listed as endangered under the U.S. Endangered Species Act (ESA). Language in the ESA encourages federal cooperation with States, and provides a mechanism for funding support for States to aid in conservation of endangered species (referred to as Section 6 grants). Supported by NOAA Fisheries Section 6 grants received by the State of Hawai‘i, Cascadia Research Collective (CRC) was contracted in 2016 and again in 2020 to assist with these efforts, undertaking field studies and analyses related to this population of false killer whales. Here we report on the outcome of those efforts from 2020 through 2022, and also include results from field activities during this period supported by other funding sources.

Pandemic-related travel restrictions imposed shortly after the contract was issued led CRC to begin ‘rapid response’ efforts off Hawai‘i Island when false killer whales were reported or when working conditions were particularly suitable for working offshore or in northern parts of the study area, where encounter rates with false killer whales are higher. After travel restrictions had eased, CRC resumed typical multi-week intensive field efforts in December 2020, but continued a combination of rapid response and multi-week field efforts through the end of the contract.

Over the three-year period CRC had 30 encounters with MHI insular false killer whales and obtained identification photos of 110 unique individuals (approximately two-thirds of the estimated population). Of these 30 encounters, 19 were from rapid-response efforts and 11 were from directed field projects. One-third of CRC encounters were of groups that were re-found by tracking individuals that had been satellite-tagged in a previous encounter. Near real-time information from tagged animals was also provided to researchers with the Pacific Whale Foundation (PWF), resulting in the contribution of three additional encounters in the Maui Nui area. When combined with photo contributions from PWF and other researchers as well as community science contributors, a total of 145 unique individuals were identified from 86 encounters over the three-year period. Of these, 10 had not been previously documented, with nine of the 10 individuals considered not distinctive or slightly distinctive, suggesting slow recruitment to the population through births rather than the discovery of new social groups. Photo-identification data from 2020 and 2021 were combined with identifications available from 1999 through 2019 in an analysis to identify the number and membership of social clusters. This analysis showed there are four discrete social clusters within the population, and a manuscript describing these analyses and results was submitted for publication (Mahaffy et al. in review). Photo-identification data from 2020 and 2021 were also provided to researchers at the Pacific Islands Fisheries Science Center (PIFSC) for ongoing analyses to estimate abundance and population trends spanning 1999 through 2021.

Location data were obtained from 16 LIMPET (Low-Impact Minimally-Percutaneous External-electronics Transmitter) satellite tag deployments, including individuals from all four social clusters. Data from these deployments were combined with tag data from 2007-2019 to examine spatial use by cluster. As was the case with earlier analyses, results showed cluster-specific spatial use. Although there is overlap of all four social clusters, particularly off windward waters of Maui and Moloka‘i, clusters varied in their spatial use by distance from

shore, in relation to seafloor depth, and in terms of the proportion of time they spent in windward or leeward waters around the islands. Location data were also provided to PIFSC to estimate cluster-specific capture probabilities for the ongoing abundance estimation effort.

Between 2020 and 2022, 28 skin and blubber biopsy samples were obtained, including samples from all four clusters. Sub-samples of all were provided to the University of Hawai‘i Health and Stranding Lab for ongoing analyses of blubber histology and hormone chemistry. Eighteen of the samples were from individuals that had not been previously biopsied (all from Clusters 3 and 4); skin subsamples of these were sent to the Southwest Fisheries Science Center to determine sex and mitochondrial haplotype and incorporated into a larger analysis of sex and haplotype distribution by social cluster presented by Mahaffy et al. (in review).

Overall, results obtained over this three-year period will allow for more robust estimation of population abundance and trends, as well as characterization of population health, spatial use, and age and sex makeup of the population.

Introduction

In Hawaiian waters, false killer whales feed on large pelagic and reef-associated game fish (Baird et al. 2008; Baird 2016), and interactions with fishermen (e.g., depredation of catch) have occurred since at least the early 1960s (Pryor 1975). High levels of site fidelity based on photo-identification (Baird et al. 2008) and results from genetic analyses (Chivers et al. 2007) both indicate a relatively small resident population around the main Hawaiian Islands that is demographically isolated from other populations. This population was first recognized as a distinct stock in 2009 (Carretta et al. 2009). Based on evidence of fisheries-related injuries (Baird and Gorgone 2005), high levels of persistent organic pollutants (Ylitalo et al. 2009), and evidence of a population decline (Reeves et al. 2009), in 2009 the Natural Resources Defense Council submitted a petition to NOAA Fisheries to list this population under the Endangered Species Act (ESA). A status review was conducted in 2010 (Oleson et al. 2010), and in 2012 the main Hawaiian Islands (MHI) insular population of false killer whales was listed as endangered under the ESA. The most recent abundance estimate for this population is from 2015, with an estimated 167 individuals (95% CI = 128-218) in the population in that year (Bradford et al. 2018).

Endangered species of whales and dolphins in U.S. waters are managed by NOAA Fisheries, but Section 6 of the ESA provides a mechanism to support states to cooperate with NOAA in the conservation of endangered species. In 2015, and again in 2019, the State of Hawaiʻi received Section 6 grants from NOAA Fisheries to support the cooperative conservation and management of false killer whales in Hawaiian waters. In 2016 and 2020 the State provided contracts to Cascadia Research Collective (CRC) to assist with these efforts, undertaking field studies and analyses of associated data to contribute to abundance estimation, and to understand spatial use, social organization, and threats to the population. Work carried out under the first (2016) contract was used to better describe spatial use, including how it varied by social cluster, and how it overlaps with nearshore fisheries (Baird et al. 2019, 2021a). Importantly, the contract supported multi-week field efforts targeted in areas that had limited prior field work (off Oʻahu in 2016 and 2017, Lānaʻi in 2017 and 2018, and off Kohala, Hawaiʻi Island, in 2017) to increase sample sizes of photographic, tag, and biopsy sample data from rarely-sampled groups. This approach was particularly productive, with 22 false killer whale encounters, 14 LIMPET satellite tags deployed, and 22 biopsy samples obtained (Baird et al. 2019). Combined with community science photo contributions, this effort provided a much better understanding of social clusters and their spatial use within the population, particularly increasing sample sizes of tag, biopsy, and photographic data from poorly-sampled clusters (Baird et al. 2019). This better understanding of social clusters was used to inform analyses of persistent organic pollutants and stable isotopes from biopsy samples (Kratofil et al. 2020). Additionally, an analysis of false killer whale spatial use in relation to fishing effort by Commercial Marine License (CML) holders was used to identify which areas fishermen are most likely to interact with (e.g., depredation or bycatch) false killer whales (Baird et al. 2021a).

A second contract was issued in January 2020 to build on these field efforts and analyses. Shortly after the contract was issued, pandemic-related closures and travel restrictions were put in place, potentially disrupting the ability to undertake field work in 2020. Fortuitously, during the previous two years CRC had trained a key Kona-based member of the research team in biopsy sampling and LIMPET satellite tagging. This key team member had access to a research vessel in 2020 and in subsequent years, and as a result we were able to adopt a new field research strategy. This involved undertaking day trips out of Honokōhau Harbor in response to reports of false killer whales from community members, or to take advantage of particularly ideal sea conditions (i.e., when conditions would allow for surveying offshore or far to the north where false killer whale encounter rates are higher). We refer to these efforts hereafter as 'rapid response' field work. As travel restrictions eased later in 2020 we were able to resume our regular multi-week field efforts, but continued in 2021 and 2022 with a combination of rapid response and our regular multi-week field efforts. Overall, this combined approach was particularly productive during the three-year period of the contract, with 33 false killer whale encounters. These included individuals from the MHI insular population, the northwestern Hawaiian Islands population (Baird et al. 2013a), and the pelagic population, with 19 satellite tags deployed (one on a pelagic individual[1] and 18 on individuals from the MHI insular population, although data were only obtained from 16), and 33 biopsy samples obtained, 28 of which were from MHI insular individuals.

Here we outline details on field work and analyses undertaken from 2020 through 2022. Although the State of Hawaiʻi contract issued to CRC in 2020 is the primary source of funding for this work, we also include sighting information and tag data from false killer whales encountered over this period obtained during projects supported in whole or in part by the U.S. Navy (off Kauaʻi in February 2020 and August 2021), by the NOAA Bycatch Reduction Engineering Program (off Lānaʻi in December 2020), and by the Pacific Islands Fisheries Science Center (off Hawaiʻi Island). While field work supported by the PIFSC grant was primarily focused on pelagic false killer whales, groups of false killer whales from the main Hawaiian Islands insular population were also encountered under that effort.

Methods

Field methods and photo contributions

Two types of field efforts were undertaken during the contract period, both using a 24' rigid-hulled Zodiac with a custom-made bow pulpit. Rapid-response efforts based out of Kona began in May 2020 in response to pandemic travel restrictions and continued through the end of 2022. These involved one of our Kona-based primary research crew members initiating survey efforts (with from one to four individuals assisting) when calls came in from community members about false killer whales in the area, or when weather conditions were particularly suitable for getting far offshore or to the north. Rapid response efforts thus could include either multiple days in one week or multiple weeks between days on the water. Dedicated field efforts, involving a larger team and daily on-water efforts for one to two weeks were restarted in December 2020 and were undertaken off Lānaʻi (in December 2020, supported in part by a NOAA Bycatch Reduction Engineering Program grant to the University of California San Diego) and off Hawaiʻi Island (in April/May 2021, November 2021, June 2022, and October 2022). Surveys were non-random and non-systematic, with the research vessel attempting to cover as broad an area as possible while remaining in areas with good working conditions (i.e., <

[1] See Fader et al. (2021)

Beaufort 3 sea conditions), while simultaneously attempting to minimize spatial and temporal biases. This was done by minimizing overlap in survey tracklines within a field project, maximizing spatial extent of coverage when conditions allowed, and alternating surveys in different depths at different times of day (Baird et al. 2013b). Additionally, field work was undertaken off Kauaʻi in February 2020, August 2021, and August 2022 supported by funding from the U.S. Navy Pacific Fleet (see Baird et al. 2021b), and false killer whales were encountered during two of these efforts.

In addition to these field efforts, photographic data were obtained from both community science contributions (particularly tour vessels) and other researchers working in the islands (primarily Pacific Whale Foundation (PWF) off Maui and Lānaʻi, but also including Pacific Islands Fisheries Science Center off Oʻahu, and the University of Hawaiʻi Marine Mammal Research Program (MMRP) working off Oʻahu and Hawaiʻi Island), as well as any stranded individuals from the Health and Stranding Lab of the University of Hawaiʻi (UH). Community science contributions were encouraged by both promoting the value of submitting photos on social media[2], inviting crew from local tour operators to join us on the water during field activities, and by working directly with contributors to provide feedback on the sighting history of individual whales or dolphins identified in photos. When multiple community science sources contributed photos of the same group of false killer whales in one area in one day (e.g., off the Waiʻanae coast of Oʻahu), photos were pooled into a single encounter.

During each encounter we recorded information on sighting cue (i.e., splash/blow/fin, radio call from another boater, location data from a previously satellite-tagged individual, acoustic cue from Navy hydrophone range, see Baird et al. 2021b), encounter start and end times and locations (recorded on a GPS), start and end behavior and direction of travel, group size (minimum, best, maximum), the spatial extent of the group, and any instances of prey captures. Given the wide spatial spread of false killer whale groups (Baird et al. 2008; Bradford et al. 2014), when more than one group of false killer whales was encountered on the same day, the two groups were combined into a single encounter for analysis purposes, and encounter parameters (end time, group size, spatial spread) were adjusted accordingly. When field personnel allowed, we typically had three photographers attempting to obtain photos of every individual present, including head photos (for identification of mouthline scarring possibly associated with fishery interactions, see Baird et al. 2017), and photos of the dorsal fin and peduncle for individual identification. When possible, photos of prey were also taken to confirm species, and if floating prey parts were observed they were collected for genetic confirmation of species. During dedicated field efforts starting in November 2021 we also began obtaining high-speed gimbal stabilized video from some encounters using a Canon R5 camera and a DJI RS2 gimbal stabilizer.

The primary choice of other types of sampling to be undertaken during any particular encounter (i.e., biopsy sampling, deploying LIMPET satellite tags, or drone operations to obtain images for photogrammetry) depended on a variety of factors. The behavior of the group (e.g., how fast they were traveling, how predictable surfacing patterns were, and how much interest they showed in the research vessel) influenced the likelihood of successfully collecting biopsy

[2] https://tinyurl.com/5fnxn479

samples, deploying tags, or obtaining footage from drone operations. The social cluster present (see Baird et al. 2012) and the identity of individuals present (confirmed by comparison with either an on-board photo-ID catalog or by sending photos back to an on-land matcher to determine identities) also influenced sampling priorities, as some social clusters had larger sample sizes of tag deployments or biopsy samples available, and thus may have been lower priority for tagging or biopsying. Whether any individuals in the group currently were tagged also influenced sampling priorities (e.g., if a group already had two or more tagged individuals, biopsy sampling or drone operations were given higher priority).

Biopsy sampling

Biopsy samples were collected with a 45-kg pull crossbow and Ceta-dart biopsy darts, with gas-sterilized stainless steel biopsy tips measuring 8 mm in diameter and penetrating to a depth of 18-20 mm. The target area for biopsy samples was the area below the dorsal fin. After collection, biopsy samples were stored on ice while on the research vessel, then subdivided and frozen once back on land. One-third of the skin was removed and sent to the Southwest Fisheries Science Center for genetic analyses, to determine sex and mitochondrial haplotype of individuals not previously biopsied (see Martien et al. 2014, 2019), and for all individuals for eventual inclusion into an epigenetic aging analysis (Martien et al. in prep). One-third of the skin of samples collected through 2020 was removed and sent to Florida International University for incorporation in trophic analyses using stable isotopes (Kiszka et al. in prep). The remaining skin and blubber were sent to the University of Hawaiʻi Health and Stranding Lab for long-term archiving and for analyses of blubber histology and hormone chemistry (Phipps et al. 2023, Phipps et al., in prep).

LIMPET satellite tag deployments

LIMPET satellite tags used were primarily location-only SPOT6 tags (Wildlife Computers, Redmond, WA), but one SPLASH10-F tag (which also recorded Fastloc®-GPS locations) was deployed during a U.S. Navy funded project off Kauaʻi. Tags were deployed with a Dan-Inject pneumatic projector and attached with two gas-sterilized 6.7 cm surgical grade titanium darts with backward facing petals. The target area for LIMPET tags was the dorsal fin. LIMPET tags were programmed prior to each dedicated field effort and programming was undertaken periodically throughout the year for rapid response efforts, taking into account satellite pass predictions (from Argos), battery lifespan considerations, and the value of using tag locations to relocate groups on subsequent days if the tagged group returned to the study area. SPOT6 tags were set to transmit up to 60 times per hour and were programmed to transmit 12 h/day for the first 60 days, in two blocks of time. These were one six- or seven-hour period in the morning (depending on the year), and another five- or six-hour period in the evening, both during periods of good satellite overpasses. After 60 days, tags were duty cycled to reduce the number of hours of transmissions (to a four-hour block in the morning and a three-hour block in the evening), and after 100 days to two one-hour blocks, one in the morning and one in the evening, corresponding to the hours of peak satellite overpasses. The SPLASH10-F tag transmitted 16 hours per day in two eight-hour blocks, with up to 1600 transmissions per day. In addition to Argos locations, this tag also recorded Fastloc®-GPS locations up to twice per hour and behavioral information, with a priority for Fastloc®-GPS locations. Near-real time location information from tagged animals was often used to re-locate groups on days subsequent to tagging, including providing locations to collaborating researchers with PWF when tagged whales were passing through their study area off Maui and to MMRP/PWF when they were working jointly off Lāna‘i.

Drone operations and photogrammetric measurements

Drone operations were undertaken using a DJI Mavic 2 Pro. A custom-built datalogger was attached to the drone and recorded lidar altitude measurements, GPS, and tilt via an inertial measurement unit continuously to a CSV file during each flight (Dawson et al. 2017). Each file from the datalogger was synced to the flight log created by the DJI Mavic 2 Pro to determine the altitude measurements at each timestamped image. Still images were extracted from the video from each encounter, saved with the timestamp, and synced with the flight log. For each image, the radial distortion was corrected by using the OpenCV calib3d module in AragoJ using a camera calibration profile we generated using the Mavic 2 (Aleixo et al. 2022). Images for measurements were shared with Pacific Whale Foundation researchers for a collaborative project on body condition.

Photo-identification, population identity, and social cluster analyses

Photos taken during encounters were sorted by individual, matched and added to the photo-identification catalog using the methodology described in Baird et al. (2008, 2012). Population identity (i.e., northwestern Hawaiian Islands population, pelagic population, or main Hawaiian Islands insular population) was determined based on association with previously documented groups. Distinctiveness of individuals within each encounter were rated on a scale of 1 to 4 (1= not distinctive, 2 = slightly distinctive, 3 = distinctive, 4 = very distinctive) and the best photo of each individual from each encounter was rated for photo quality (1 = poor, 2 = fair, 3 = good, 4 = excellent), following Baird et al. (2008). Individuals with mark changes (e.g., new nicks or notches on the leading or trailing edge of the dorsal fin) from previous sightings were noted, particularly to assess evidence of prior fishery interaction (see Baird et al. 2015, 2017).

Individuals documented during 2020-2021, as well as photos obtained from 1999 through 2019, were incorporated into a larger analysis to determine the number and membership of social clusters in the population. Details on the methodology of this study are presented by Mahaffy et al. (in review) so are only briefly addressed here. Association analyses were undertaken both in SOCPROG 2.9 (Whitehead 2009) using MATLAB and in R v. 4.2.1 (R Core Team 2022). In both, dyadic (pair-wise) associations were measured on a scale of 0 – 1.0 (ranging from individuals never seen in association to individuals always associated) with a half-weight index (HWI) to account for situations where not all individuals were photographed and identified (Cairns and Schwager 1987; Whitehead 2008; Farine 2013). Individuals were considered associated if they were in the same group. Data used to analyze associations and determine the most appropriate clustering algorithm (see below) were restricted to individuals seen on five or more days over the 1999-2021 period and considered at least slightly distinctive (highest distinctiveness ≥ 2) with fair or better quality photos (photo quality ≥ 2) to minimize errors associated with lower quality data (Whitehead 2008). The decision to include slightly distinctive individuals and fair photo qualities was based in part on the characteristics of the study population (i.e., a small resident population with limited range composed of well-known individuals), all of which increase capture probability (Urian et al. 2015).

To determine the number and membership of clusters in the population, we tested six different community detection algorithms using community assignment functions within the igraph package in R (v.1.3.4) (Csardi and Nepusz 2006), and then used an approach outlined by Shizuka and Farine (2016) to determine which algorithm best represents actual social groups (i.e., clusters) within the restricted dataset. For each algorithm, the modularity of the particular cluster assignment was calculated using the modularity (Q) function in the igraph package, with values greater than 0.3 indicating that clusters are useful in describing how individuals in the population associate (Newman 2004; Csardi and Nepusz 2006). The robustness of community assignments was measured through community assortativity (r_{com}) and calculated in R using the igraph, assortnet (v. 0.12), and asnipe (v. 1.1.16) packages for each cluster assignment method with 1,000 bootstrap replications (Csardi and Nepusz 2006; Farine 2014, 2016; Shizuka and Farine 2016). This method resamples observations of groups with replacement and generates new community assignments. As noted by Shizuka and Farine (2016), the value of r_{com} is 1 when all bootstrap replicates provide the same community assignments and approaches zero when community assignments in the replicates are random compared to the original network. We used a combination of modularity and community assortativity values to choose the most appropriate (best) algorithm for determining the number of clusters and cluster membership. A weighted social network diagram was used to visualize associations within the study population for the algorithm with the highest modularity and r_{com} values.

Cluster-specific spatial use and satellite tag data analyses

Cluster-specific spatial use was evaluated both using photo-identification data (i.e., the island area that individuals from specific clusters were documented) and satellite tag data. Details on satellite tag data processing are available in Kratofil et al. (2023, Supplementary B) so are only briefly outlined here. Kalman-processed Argos location data were processed through the Distance-Angle-Rate filter of the Douglas Argos Filter (Douglas et al. 2012) to remove erroneous locations. After processing, remaining locations were fit to a continuous-time correlated random walk model via crawl v2.2.3 (Johnson et al. 2008; Johnson and London 2018) to estimate locations at regular intervals. Crawl locations were re-routed around land using the pathroutr package (London 2021). Cluster-specific density maps were generated by summing all crawl locations (at 1-hour intervals) within grid cells on a grid encompassing the entire main Hawaiian Islands. Crawl locations interpolated over periods of one or more days without underlying Argos locations were removed prior to generating density maps to prevent artificially "dense" areas. Pseudoreplicated pairs (i.e., tagged individuals acting in concert) were accounted for by removing the individual with the shortest track from each pair prior to analyses; this was conducted for only same-cluster pseudoreplicate pairs given the relevance for cluster-specific spatial use (see Baird et al. 2010, 2012 for details on definition of pseudoreplicate pairs).

A comparison of a few simple spatial use metrics was also made to evaluate cluster-specific spatial use. Re-routed locations were populated with the following variables: distance from shore (using sf; Pebesma, 2018), seafloor depth from the main Hawaiian Islands multibeam bathymetry grid[3] (using stars; Pebesma, 2022), and position on the windward or leeward side of the islands. Satellite tag location data were also provided to the PIFSC for estimating cluster-specific capture probabilities (Badger et al. in prep), and to a Ph.D. research project at Oregon State University for a study of false killer whale spatial use.

Results

Encounters and photo-identification

Over the three-year period (2020-2022) with funding from multiple sources, CRC was on the water 157 days, with 35 days off Kauaʻi, 16 days off Lānaʻi and Maui, and 106 days off Hawaiʻi Island. Combined, this represented 19,806 km of effort. False killer whales were encountered on 33 of those days, with sightings on three days (in February 2020 and August 2021) off Kauaʻi, one day off Maui and five days off Lānaʻi (all in December 2020), and 24 days off Hawaiʻi Island (Table 1, Figure 1). Two of the three encounters off Kauaʻi (both from February 2020) were groups from the northwestern Hawaiian Islands population, and one encounter off Hawaiʻi Island (in May 2020) was of individuals from the pelagic population, with the remaining 30 encounters being individuals from the main Hawaiian Islands insular population. One-third of those encounters (10 of 30) were initiated in response to radio calls from other boaters, and another third (10 of 30) were in facilitated by relocating a group of tagged individuals using the Argos location information (see below). Almost two-thirds of the encounters (19 of 30) were from rapid response efforts. Predation events were recorded in 17 of the 30 encounters with individuals from the MHI population, primarily involving mahimahi (*Coryphaena hippurus*) and occasionally involving ahi (*Thunnus albacares*) and ono (*Acanthocybium solandri*). One predation event involving kanpachi (*Seriola rivoliana*) was also documented.

A total of 49,629 photographs were taken during CRC false killer whale encounters, drone footage was obtained in four encounters, and high-speed video footage was obtained from two encounters[4]. Photo matching from the 30 CRC encounters with MHI insular false killer whales in this period resulted in 308 identifications, and of those, 292 were of fair or better photo quality. The number of identifications with fair or better-quality photos per encounter ranged from three to 28 (median=8; Table 2). Including all distinctiveness categories, 110 different individuals from the MHI population were documented over the three-year period. Of these, only five were new to the catalog (i.e., had not been previously documented), with a single new individual documented in five different encounters, three in 2020, one in 2021, and one in 2022 (Table 2). All of the new individuals were considered either not distinctive (two individuals) or slightly distinctive (three individuals), suggesting that they were relatively young, rather than older individuals that had escaped being photographed for an extended period (Table 2). New individuals were documented from each of the four social clusters (see below).

In addition to CRC encounters, photos of MHI insular false killer whales from 2020

[3] http://www.soest.hawaii.edu/hmrg/multibeam/bathymetry.php
[4] Examples of high-speed video footage are available at https://youtu.be/tgtB97H3GpE, https://youtu.be/2vU3X64UKmg and https://youtu.be/lIrK8xB9Is8

through 2022[5] were also received from other sources (in decreasing order of contributions): Pacific Whale Foundation[6], Wild Side Specialty Tours, Dolphin Excursions Hawaiʻi, the University of Hawaiʻi Marine Mammal Research Program, PIFSC, Kaimana Ocean Safaris, Explore Kauaʻi Scuba, Holoholo Charters, Captain Steve's Rafting Adventures, and 20 different individuals. From these, we found 293 identifications with fair or better photo quality, representing 109 different individuals, including 35 not documented during CRC efforts. Photos from an individual that was found dead on Maui on 12 February 2021 were also contributed by the Health and Stranding Lab of UH. Combining both CRC and contributed photos resulted in a total of 145 different individuals documented over the three-year period with fair or better-quality photos. Of these, 10 individuals were new to the catalog in the 2020-2022 period (Table 3), including four non-distinctive individuals, five slightly-distinctive individuals, and one distinctive individual. By distinctiveness category, of the 145 individuals, 13 were considered not distinctive, 38 were considered slightly distinctive, 58 were considered distinctive, and 36 were considered very distinctive.

Fifty-five changes to markings on the leading and/or trailing edge of the dorsal fin were documented on 52 of the 145 individuals. Changes to the dorsal fin ranged from subtle (e.g., the addition or modification of small notches) to significant (e.g., addition of large notches or changes in notch pattern that significantly alter the appearance). Significant mark changes to the dorsal fin were documented in eight individuals, with the gap between re-sightings ranging from 153 to 4,103 days (median=535). All but two of the individuals with significant mark changes were resighted more than a year apart, and it is possible that these individuals underwent several mark change events between re-sightings, highlighting the importance of increased survey coverage. The majority of all mark changes from 2020-2022 (56.4%) were observed in individuals that had not been resighted for more than a year, but changes were also documented over timespans as short as 11 days. One such individual, HIPc310, was documented with a fresh line injury to the base of the leading edge of the dorsal fin in October 2016 that appeared to be completely healed when seen on 2 November 2021, but was resighted with a fresh re-injury to the fin 14 days later (Figure 2). This re-injury suggests that while the skin had healed over the wound first documented in 2016, the connective tissue that was severed had not been completely repaired, leaving the area weakened and prone to re-injury. Subsequent sightings of this individual in 2022 show increased bending of the fin, suggesting that the fin may eventually collapse completely, as has been documented for other individuals involved in fishery interactions (Baird and Gorgone 2005; Baird et al. 2015; Stack et al. 2019). One individual was also seen with a new notch at the base of the leading edge of the dorsal with scarring extending diagonally along the left side of the dorsal fin to the tip, likely resulting from fishing line cutting into the leading edge and wrapping around the fin as the animal moved against the line.

Of the 145 individuals documented, there were notable long gaps in sightings of some individuals, particularly for Cluster 2. Of the 28 Cluster 2 individuals identified between 2020 and 2022, 15 had been last photographed more than four years earlier (ranging from 4.6 to 11.2

[5] This includes all photos obtained through January 20, 2023 - additional community science photo contributions from later in 2022 have been received but are not yet matched.
[6] Near-real time location data from tagged whales resulted in three encounters by Pacific Whale Foundation off Maui, Lānaʻi, and Kahoʻolawe.

year previously), 10 of which had undergone mark changes in intervening years. The individual that was found dead on Maui in February 2021 was identified as HIPc111, a Cluster 4 individual first documented off Maui in November 2000, and subsequently documented off Maui (in 2006 and 2018), Lānaʻi (in 2018, 2019, and 2020), and off Hawaiʻi Island (in 2009 and 2012).

Biopsy samples

Of 33 total false killer whale biopsy samples, 28 were from individuals from the MHI insular population (Table 4). Of these, 18 were of individuals that had not been previously biopsied. Ten of those 18 were from Cluster 4, the social group with the smallest number of biopsy samples available. Genetically-determined sex and mitochondrial haplotypes from biopsy samples were incorporated into a larger analysis of sex and haplotype distribution by social cluster presented by Mahaffy et al. (in review). Individuals that had been previously biopsied were sampled between 1.7 and 22.5 years earlier (median = 10.9 years).

Identification of social clusters

Photo-identification data obtained during 2020-2021 from field efforts, other research organizations, and community science contributions were incorporated into analyses of social clusters including data from 1999-2019. Results from this work are presented in detail in Mahaffy et al. (in review) but main points are summarized here. Between 1999 and 2021, false killer whales from the main Hawaiian Islands insular population were photographed on 416 days, resulting in 3,429 identifications of 349 individuals. When restricted to encounters with at least one individual meeting our minimum photo quality and distinctiveness criteria (i.e., at least slightly distinctive with fair or better-quality photos), there were encounters on 382 days, with 2,915 identifications of 292 individuals. Of these, identifications were obtained predominantly by CRC (1,196), Wild Side Specialty Tours (366), PWF (286), Wild Whale Research Foundation (213), Hawaiʻi Whale Research Foundation (152), and NOAA Fisheries (141), with the remaining 561 identifications contributed by 66 different organizations and individuals. Using individuals seen on five or more occasions, the six community assignment functions generated 4 to 6 (mode = 4) clusters, with modularity ranging from 0.578 to 0.605, and r_{com} (community assortativity) ranging from 0.913 to 0.968. The three community assignment algorithms that had the highest modularity and r_{com} values (Louvain, Fastgreedy and Walktrap in decreasing order) produced identical results in terms of number (four) and composition of clusters: 62 individuals in Cluster 1, 15 individuals in Cluster 2, 60 individuals in Cluster 3 (which included the individuals from Cluster 5 identified by Baird et al. 2019), and 37 individuals in Cluster 4 (Figure 3). Cluster membership between the current study and the clusters identified by Baird et al. (2012) showed little change to Clusters 1, 2 and 3. Of the four peripheral clusters identified in the Baird et al. (2012) study, two were absorbed into Cluster 3 and two combined to form Cluster 4 in the current study. We also re-assessed cluster membership for the four individual false killer whales from this population that had stranded prior to the study period (from 27 November 2010, 6 October 2013, 7 November 2015, and 28 September 2016) that had been previously matched to the photo-identification catalog. Cluster membership did not change for any of these individuals – all were identified as members of Cluster 3.

Cluster-specific spatial use

Cluster-specific spatial use from photo-identification was assessed with the 1999-2021 dataset used in the cluster analyses (above), and showed that Cluster 1 was seen off all island areas, Cluster 2 was primarily seen off Hawai‘i Island, Cluster 3 was primarily seen off O‘ahu and Hawai‘i Island, and Cluster 4 was primarily seen off Maui Nui (Figure 4).

A total of 18 LIMPET satellite tags were deployed in 20 attempts (two tags were lost) on MHI insular individuals, although data were only obtained from 16 of 18 deployed tags (Table 5). Tags were deployed on individuals from all four social clusters and transmission durations ranged from 12 to 188 days. Excluding individuals acting in concert, deployments during this period bring the total number of tag deployments for this population to 49, with 4 to 27 deployments per cluster (Table 6). One of the tags (PcTag074) was a SPLASH10-F tag, only the second SPLASH10-F tag deployed on a false killer whale. This tag transmitted 9.2 days of dive behavior data that are being incorporated into a larger analysis of false killer whale diving and night-time behavior (Shaff et al. 2022). Location data from tags deployed in 2020 and 2021 were incorporated into an analysis identifying biologically important areas for this population (Kratofil et al. 2023). Details are presented by Kratofil et al. (2023, supplemental file A) and thus are not included here.

Maps showing movements of individuals tagged during 2020 through 2022 are shown in Figures 5 through 8. The longest deployment (PcTag075) was over 188 days, on an individual from Cluster 1 (Figure 5). Movements over that period spanned the entire main Hawaiian Islands, although it should be noted that individuals tagged for much shorter periods (i.e., PcTag076 and PcTag078, at 57 and 44 days, respectively) also covered the entire span of the main Hawaiian Islands (Figures 5, 7). By contrast, one individual from Cluster 3 tracked over a 68-day period that overlapped temporally with the aforementioned PcTag076 and PcTag078 remained associated only with Hawai‘i Island for the entire period (PcTag077; Figures 7, 9). Both Cluster 1 (Figure 5) and Cluster 3 (Figure 7) individuals were documented moving over the entire span of the main Hawaiian Islands. Cluster 1 tagged whales made similar use of island areas within their range, with some differences based on varying deployment durations (i.e., shorter deployments didn’t use as many island areas as the longest deployment; Figure 5). This same pattern was seen for Cluster 3 and Cluster 4 tagged whales (Figures 7, 8), and especially the case for Cluster 4 where all three tagged whales remained strongly associated during the common deployment period using a very restricted area within O‘ahu and Maui Nui (Figure 8). In contrast, the two Cluster 2 tagged whales exhibited different movement patterns (Figure 6). PcTag070 used windward Maui Nui and northwest Hawai‘i Island extensively, as has largely been the case for all previous Cluster 2 tag deployments (CRC unpublished). PcTag083 immediately moved away from Hawai‘i Island post-tagging and spent more time around Maui Nui and O‘ahu than has been documented previously for Cluster 2 individuals; this individual was associated with PcTag082[7] for most of its deployment period when using the O‘ahu/Maui Nui areas.

[7] PcTag082 was still transmitting as of February 7, 2023, and thus data on movements of this individual are not included here.

Maps of cluster-specific density reveal similar range-wide spatial use patterns for Clusters 1 and 3 and more distinct range-wide spatial use patterns for Clusters 2 and 4 (Figures 10-13). High density areas for Cluster 1 are more widely dispersed, and include windward Maui Nui, Penguin Bank, nearshore O‘ahu, and northwest Hawai‘i Island (Figure 10). Cluster 2's high-density areas are largely restricted to the northwest edge of Hawai‘i Island with some extensive use of northeast Maui (Figure 11). For Cluster 3, the most prominent high-density area is in the north end of the Kaiwi Channel, in an area that spreads along the shelf between east O‘ahu and Moloka‘i; high-density areas for this cluster are also apparent along the northwest shelf/slope edge of Hawai‘i Island (Figure 12). Cluster 4 high-density areas are also relatively restricted in space, with hotspots off the southwest side of Lāna‘i and the Kaiwi Channel (Figure 13).

The comparison of spatial metrics among the four social clusters indicate that clusters broadly cover the same range in terms of distances from shore (Figure 14), but that the peak densities vary among clusters in terms of distance from shore. Their use of areas with different bottom depths also differs (Figure 15), suggesting that are cluster-specific differences relative to seafloor topography that varies among the islands. For example, Clusters 1 and 4 had a peak in their seafloor depth distribution at shallow depths (<200 meters), and then another peak at intermediate depths (around 500-600 meters) before leveling off. In contrast, Clusters 2 and 3 did not use shallow waters as much as Clusters 1 and 4, with the mass of their distributions ranging between 500 and 1,000 meters (Figure 15). There were also cluster-level differences in the proportion of time spent on leeward versus windward sides of the island (Figure 16). Cluster 1, and especially Cluster 4, used leeward sides of the island more than windward, whereas the opposite trend was apparent for Clusters 2 and 3 (Figure 16).

Discussion

Overall, field efforts from 2020 through 2022 were very productive, with more false killer whale encounters, tag deployments, and biopsy samples obtained than in the previous three-year Section 6 contract to CRC (Baird et al. 2019). We attribute this success, despite pandemic-related restrictions on travel in the first year, in large part to combining rapid response efforts with our prior approach of focused multi-week field efforts. This approach takes advantage of good weather windows and the large community of individuals on the water off Hawai‘i Island that may share sighting information. It should be noted, however, that while this approach works for increasing sample sizes (of photos, tag deployments, and biopsy samples) of Clusters 1, 2, and 3, Cluster 4 is primarily encountered around Maui Nui (Figure 8) and particularly favors areas to the southwest of Lāna‘i (Figure 13). Thus, directed research efforts to work in high-density areas are still needed to increase sample sizes for Cluster 4.

On a broad spatial scale, all tagged individuals largely exhibited similar spatial use and movement patterns as previously tagged whales from their corresponding clusters (see e.g., Baird et al. 2012, 2019), recognizing that minor differences are likely driven by varying deployment durations. One exception to this was PcTag083, a deployment on an individual from Cluster 2 (Figure 6). While one previous Cluster 2 tagged animal did move away from Hawai‘i Island and traveled around O‘ahu and Maui Nui for a brief period of time, PcTag083 spent more time around O‘ahu and Maui Nui (along with PcTag082) for longer than has been documented to date. Collectively, these patterns highlight that additional satellite tag data collected from all clusters during this project period has advanced understanding of cluster-specific spatial use by either reinforcing known patterns or revealing new patterns. For clusters with larger sample sizes, the additional tag location data will allow for better analysis and inference on the influence of the physical environment versus group-level processes (i.e., cluster membership) in determining cluster-specific spatial use patterns. For clusters with smaller sample sizes, the additional tag deployments provide further insight into the spatial social structure of the population and spatial overlap (or lack thereof) among social clusters. Interestingly, the density patterns documented in the complete tag data set (Figures 10 through 13) mirror what is seen in the social network, where Clusters 2 and 4 are more isolated in the social network and Clusters 1 and 3 more connected within the network (Figure 3). It is possible, however, that this may be an artifact of the small sample size of tag deployments for Clusters 2 and 4 (Table 6), and more deployments are needed on individuals in both clusters.

While our sample sizes of tag deployments for Cluster 1 and 3 are relatively large (27 and 14 deployments, respectively, after accounting for pseudoreplication), results from a period with overlapping data from multiple individuals is particularly informative in terms of the value of additional tag deployments on both clusters. During the period from September to December 2021 we obtained overlapping location data from five different individuals, two from Cluster 1 (PcTag075 and PcTag076), and three from Cluster 3 (PcTag077, PcTag078, and PcTag079). While we might expect individuals from the two clusters to differ in their spatial use (see Figures 10, 12), there were striking differences in spatial use of some individuals from Cluster 3 during periods of temporal overlap. In particular, PcTag077 remained around Hawaiʻi Island for the entire 68-day period of tag transmission, repeatedly circumnavigating the island, while PcTag078 separated from PcTag077 and ended up roaming widely among the islands for the second-half of the overlap period (Figure 9). This reflects that, despite being assigned to the same cluster based on long-term association data from photo-identification, individuals within clusters do not always remain associated, indicating the existence of within-cluster spatial-social dynamics that need further investigation.

Combining community science contributions, those of other researchers (particularly Pacific Whale Foundation), and photos obtained in both rapid response and directed research efforts, resulted in the identification of 145 individuals over this three-year period, approximately 87% of the estimated abundance of this population based on the most recent abundance estimate (Bradford et al. 2018). It should be noted, however, that this includes individuals that were not considered distinctive, as well as those documented only with fair quality photos. In contrast, identifications for mark-recapture abundance analysis are typically restricted to distinctive and very distinctive individuals with good or excellent-quality photos (e.g., Bradford et al. 2018). There is a greater likelihood of missed matches for non-distinctive and slightly distinctive individuals, particularly for individuals with only lower quality photos available, given the number of individuals documented with mark changes. Combined with likely births and deaths occurring during this period, this means that the proportion of the population that we identified over this three-year period is likely somewhat lower than 87%. Our analyses assessing the number and membership of social clusters largely mitigated this by only including individuals seen on five or more occasions, but it is possible that within a shorter period some of the non-distinctive or slightly-distinctive individuals documented have accumulated marks to such an extent that they would be missed in the future.

The high rate of mark-change documented in this study reinforces the value in efforts that increase the likelihood that individuals will be photo-identified at shorter time intervals, when small mark changes are not likely to obscure matching. Of the 145 individuals, 10 new individuals were documented. The fact that nine of the 10 were considered not distinctive or slightly distinctive suggests that the likelihood of missing entire social groups (e.g., new clusters) in this population is relatively small. Although there is always a chance that a missing social group from this population does spend most or all of their time on the windward side of the islands, where there is very little research effort, the four known clusters spent substantial amounts of time on the leeward sides of the islands (ranging from ~40% to over 60%; Figure 16), and even when tracked for shorter periods, individuals do regularly move back and forth from leeward to windward sides of the islands (see Figures 5 through 8). That said, there is clearly great value in undertaking surveys on the windward sides of the islands if conditions are favorable, given the high-density areas for all four clusters in windward areas and the evidence for two clusters having higher proportions of time spent on windward sides (Figures 10 through 13; Figure 16). This would be particularly valuable for reducing the long gaps in identifications for Cluster 2. This cluster had the smallest sample size of identifications over the three-year study period, with just 42 identifications representing 28 individuals (compared to the 260 identifications of 28 individuals available for Cluster 1 – see Table 3). Notably, over half the individuals from Cluster 2 had been last documented over four years earlier, with one not being photographed for 11.2 years. Such gaps reinforce the importance of community science contributions and collaborations among researchers in studying this endangered population of false killer whales.

Collectively, the efforts of this three-year project have revealed advancements in our understanding of MHI false killer whales in a number of ways. One new prey species, kanpachi, was documented in the diet for this population, expanding a broad list of pelagic and reef-associated game fish (Table 7). Kanpachi (also known as kampachi or Almaco jack) are actively farmed off Kona in an area that overlaps with this population, and interactions with the farm have been noted for other species of marine mammals, including bottlenose dolphins (*Tursiops truncatus*) learning to get kanpachi out of the cages (Harnish et al. in press). Given the potential for future false killer whale interactions with the farm, this should be considered in environmental planning and management.

There were particular advances in our understanding of social structure and spatial use for this population, which have important implications for their management. Apparent differences in the connectivity of clusters in the social network and cluster-specific spatial use imply that spatial-social structure is an important component of overall population dynamics, which could result in disproportionate exposure to risks. However, these advancements have also identified knowledge gaps that warrant additional efforts to fill in order to adequately inform management needs. Broadly, these gaps could be addressed through (1) more targeted efforts in poorly surveyed areas that, based on satellite tag data, are frequently used by data limited social clusters (i.e., Clusters 2 and Clusters 4); and (2) the undertaking of comprehensive analyses on existing datasets to further information on population dynamics and health, social structure, and drivers of spatial use.

Understanding the factors that drive where MHI false killer whales spend their time is of critical importance for their management, as such information can directly inform overlap with pertinent risks, such as with fisheries. While previous work has identified broad-scale overlap with fisheries (Baird et al. 2019, 2021a) and some habitat relationships (Baird et al. 2012, 2021a), the results in this report have indicated that social cluster membership may play a role in where MHI false killer whales spend their time. The interface of spatial and social behaviors, which may be culturally driven, has been comparatively ignored in conservation efforts (Brakes et al. 2021), but its importance in determining where animals spend their time, and thus how they may overlap with risks, is beginning to be acknowledged (Webber et al. 2023). For example, space use decisions may be mediated by social (e.g., proximate cues of sharing information) or cultural-level processes (e.g., ultimate drivers, group-level traditions) while at the same time, opportunities for individuals to be in close proximity to, and thus interact with, conspecifics in the environment are determined by the spatial distribution of available resources (e.g., Cordeiro et al. 2018; Spiegel and Crofoot, 2016; Payne et al. 2022). Such behavioral processes are highly relevant to MHI false killer whales given their life history (e.g., strongly social, long-lived), and as are evident in their observed social structure, wide-ranging behavior, and now, more recently emerging, high-level differences in cluster-specific spatial use. Furthering our understanding on the relative importance of social factors and aspects of the physical environment (e.g., habitat, resource availability) on the movements and spatial use of MHI false killer whales is of utmost importance for their conservation and will aid in spatial predictions for management. Having a better description of their social structure, as presented here, is a start; obtaining more information on their long-term spatial use (e.g., through satellite tag deployments, especially on data-limited social clusters) and conducting more advanced analyses that comprehensively evaluate habitat versus group-level drivers (e.g., see Vachon et al. 2022) in future efforts would help address this knowledge gap. Both of these components could be fulfilled through targeted field efforts in poorly surveyed areas and through further analyses of existing datasets.

In addition to increasing our understanding of the number and membership of social clusters (Figure 3), and their differences in spatial use (Figures 14-16), analyses of biopsy samples obtained contribute to a wide variety of efforts relevant to management. Genetic sex determination is one obvious example, which feeds into both understanding social structure (Mahaffy et al. in review) and into efforts to understand the age distribution of the population. During this project period we developed a protocol (supported by a PIFSC grant) to estimate the age of individuals using photo-ID catalog information, that was originally intended for the concurrent epigenetic aging project for biopsied individuals (Kratofil et al. in review), but its application to all MHI individuals will allow for several age-relevant assessments. Knowing the sex of individuals is critical for this assessment, particularly given sex differences in growth rates (Ferreira et al. 2014). Combined this will allow for examining age structure of the population and age and sex composition of social groups (e.g., age of dispersal, population growth trends), age- and sex-specific evidence of interactions with fisheries, and age-body size and condition relationships. Analyses of biopsy samples for on-going efforts will also help inform other aspects of MHI false killer whale population and spatial ecology; stable isotopes or compound-specific fatty acids, for example, can be compared to movement data to narrow inferences on cluster-specific differences in spatial use and foraging patterns. Lastly, as noted several times above, obtaining more identifications from Clusters 2 and 4 would allow for a better understanding of the population-level social network. Currently, these two clusters are the most isolated in the social network and exhibit similar range-use patterns (i.e., restricted ranges relative to Clusters 1 and 3). Whether this observation is an artifact of low sample size, or truly a reflection of what the population is doing, cannot be appropriately verified without supplementing information on these data-limited clusters.

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Table 1. Sighting details of false killer whales encountered by CRC during dedicated field efforts and rapid response efforts in 2020, 2021, and 2022. Note, encounters off Kaua‘i were based on field work supported by the U.S. Navy.

Date	Population	Cluster*	Group size (best)	Island	Sighting Cue	Effort type
14-Feb-20	NWHI	-	10	Kaua‘i	Acoustic Detection	Directed
15-Feb-20	NWHI	-	1	Kaua‘i	Acoustic Detection	Directed
14-May-20	Pelagic	-	48	Hawai‘i	Splash, blow, or fin	Rapid response
22-Jun-20	MHI	1 & 2	17	Hawai‘i	Radio call	Rapid response
03-Jul-20	MHI	1 & 2	18	Hawai‘i	Radio tracking	Rapid response
29-Sep-20	MHI	3	8	Hawai‘i	Splash, blow, or fin	Rapid response
19-Oct-20	MHI	3	8	Hawai‘i	Radio tracking	Rapid response
15-Nov-20	MHI	3	9	Hawai‘i	Splash, blow, or fin	Rapid response
03-Dec-20	MHI	4	14	Lāna‘i	Splash, blow, or fin	Directed
05-Dec-20	MHI	4	12	Lāna‘i	Splash, blow, or fin	Directed
07-Dec-20	MHI	2	6	Maui	Radio call	Directed
08-Dec-20	MHI	4	6	Lāna‘i	Splash, blow, or fin	Directed
12-Dec-20	MHI	4	12	Lāna‘i	Splash, blow, or fin	Directed
16-Dec-20	MHI	4	15	Lāna‘i	Radio tracking	Directed
08-Aug-21	MHI	3	30	Kaua‘i	Splash, blow, or fin	Directed
05-Sep-21	MHI	1	25	Hawai‘i	Radio call	Rapid response
08-Sep-21	MHI	1	9	Hawai‘i	Radio tracking	Rapid response
15-Sep-21	MHI	1	15	Hawai‘i	Radio tracking	Rapid response
30-Sep-21	MHI	3	9	Hawai‘i	Radio call	Rapid response
07-Oct-21	MHI	3	5	Hawai‘i	Radio tracking	Rapid response
12-Oct-21	MHI	3	12	Hawai‘i	Radio tracking	Rapid response
15-Oct-21	MHI	3	5	Hawai‘i	Radio tracking	Rapid response
22-Oct-21	MHI	3	16	Hawai‘i	Radio tracking	Rapid response
07-Nov-21	MHI	3	4	Hawai‘i	Splash, blow, or fin	Directed
10-Nov-21	MHI	3	14	Hawai‘i	Radio tracking	Directed
11-Nov-21	MHI	3	16	Hawai‘i	Splash, blow, or fin	Directed
14-Nov-21	MHI	3	7	Hawai‘i	Radio call	Directed
05-Feb-22	MHI	1	15	Hawai‘i	Radio call	Rapid response
07-Jul-22	MHI	1	22	Hawai‘i	Radio call	Rapid response
18-Jul-22	MHI	1	9	Hawai‘i	Splash, blow, or fin	Rapid response
12-Sep-22	MHI	3	12	Hawai‘i	Radio call	Rapid response
13-Nov-22	MHI	2 & 3	9	Hawai‘i	Radio call	Rapid response
25-Nov-22	MHI	3	14	Hawai‘i	Radio call	Rapid response

*Cluster designations are based on Mahaffy et al. (in review).

Table 2. Number of individual main Hawaiian Islands insular false killer whales photographically identified by CRC during the study period (2020-2022) by encounter, restricted to photos of fair or better quality, with the number of new identifications (i.e., individuals not previously documented in any year) shown.

Date	# identifications all distinctiveness classes	# identifications distinct and very distinct only	# new identifications not distinct slightly distinct	# new identifications distinct and very distinct
22-Jun-20	21	16	1	0
03-Jul-20	15	12	0	0
29-Sep-20	8	7	0	0
19-Oct-20	5	5	0	0
15-Nov-20	4	4	0	0
03-Dec-20	10	7	1	0
05-Dec-20	9	6	0	0
07-Dec-20	4	2	1	0
08-Dec-20	4	2	0	0
12-Dec-20	13	5	0	0
16-Dec-20	25	15	0	0
08-Aug-21	28	19	0	0
05-Sep-21	20	15	0	0
08-Sep-21	6	6	0	0
15-Sep-21	11	11	0	0
30-Sep-21	7	4	1	0
07-Oct-21	3	2	0	0
12-Oct-21	5	3	0	0
15-Oct-21	5	3	0	0
22-Oct-21	13	10	0	0
07-Nov-21	3	2	0	0
10-Nov-21	8	6	0	0
11-Nov-21	12	7	0	0
14-Nov-21	7	3	0	0
05-Feb-22	14	11	0	0
07-Jul-22	17	13	0	0
18-Jul-22	4	3	0	0
12-Sep-22	10	7	0	0
13-Nov-22	9	5	1	0
25-Nov-22	7	4	0	0

Table 3. Summary of photo-identification data by cluster for main Hawaiian Islands insular false killer whales from 2020 through 2022, including information from CRC, other research groups, and community science contributions, restricted to photos of fair or better photo quality. Cluster designations are based on Mahaffy et al. (in review).

Cluster	# encounters*	# identifications (not excluding re-sightings)	# individuals (excluding re-sightings)	# new individuals
1	45	260	28	1
2	10	42	28	3
3	45	201	55	4
4	15	82	34	2
Total		585	145	

*Some encounters included individuals from more than one cluster, and are counted in the totals here for each cluster.

Table 4. Biopsy samples from main Hawaiian Islands insular false killer whales obtained by cluster between 2020 and 2022 with a comparison to numbers available through 2019. Note totals included for prior samples and individuals include samples obtained by CRC and PIFSC. Cluster designations are based on Mahaffy et al. (in review).

Cluster	# prior samples (2000-2019)	# individuals previously sampled (2000-2019)	# biopsies 2020-2022	# new individuals biopsied 2020-2022	Total # individuals biopsied
1	52	35	1	0	35
2	45	38	1	0	38
3	57	42	13	8	50
4	20	16	13	10	26
Total	174	131	28	18	149

Table 5. Tag deployments on main Hawaiian Islands insular false killer whales from 2020 through 2022. Cluster designations are based on Mahaffy et al. (in review).

TagID	Individual ID	Date tagged	Deploy duration (days)	Cluster	Age class	Sex	Tag type	Island tagged
PcTag066	HIPc202^	22-Jun-20	28.40	Cluster 1	Adult	Male	SPOT6	Hawaiʻi
PcTag067	HIPc159	29-Sep-20	81.05	Cluster 3	Adult	Female	SPOT6	Hawaiʻi
PcTag068	HIPc188	19-Oct-20	20.88	Cluster 3	Adult	Male	SPOT6	Hawaiʻi
PcTag069	HIPc262#	3-Dec-20	0.00	Cluster 4	Adult	Male	SPOT6	Lānaʻi
PcTag070	HIPc149	7-Dec-20	42.45	Cluster 2	Adult	Male	SPOT6	Maui
PcTag071	HIPc711	12-Dec-20	39.85	Cluster 4	Adult	Female?	SPOT6	Lānaʻi
PcTag072	HIPc511	16-Dec-20	18.22	Cluster 4	Adult	Male	SPOT6	Lānaʻi
PcTag073	HIPc377	16-Dec-20	23.84	Cluster 4	Adult	Male?	SPOT6	Lānaʻi
PcTag074	HIPc364	8-Aug-21	12.05	Cluster 3	Adult	Unknown	SPLASH10-F	Kauaʻi
PcTag075	HIPc808	5-Sep-21	187.93	Cluster 1	Juvenile	Unknown	SPOT6	Hawaiʻi
PcTag076	HIPc181	15-Sep-21	57.50	Cluster 1	Adult	Male	SPOT6	Hawaiʻi
PcTag077	HIPc277	30-Sep-21	67.90	Cluster 3	Adult	Female?	SPOT6	Hawaiʻi
PcTag078	HIPc349	15-Oct-21	44.44	Cluster 3	Adult	Female?	SPOT6	Hawaiʻi
PcTag079	HIPc577	11-Nov-21	76.78	Cluster 3	Sub-adult	Unknown	SPOT6	Hawaiʻi
PcTag080	HIPc717	5 Feb 22	0.00	Cluster 1	Juvenile	Unknown	SPOT6	Hawaiʻi
PcTag081	HIPc145*	7-Jul-22	13.45	Cluster 1	Adult	Female	SPOT6	Hawaiʻi
PcTag082	HIPc923	13-Nov-22	86ˣ	Cluster 2	Sub-adult	Unknown	SPOT6	Hawaiʻi
PcTag083	HIPc851	13-Nov-22	21.95	Cluster 2	Juvenile	Unknown	SPOT6	Hawaiʻi

^HIPc202 has been previously tagged (PcTag007 in 2008). #HIPc262 has been previously tagged (PcTag055 in 2017). *HIPc145 has been previously tagged twice (PcTag008 in 2008 and PcTag017 in 2009; see Figure 3 in Baird et al. (2012)). ˣStill transmitting as of February 7, 2022.

Table 6. Summary of satellite tag deployments with location data for main Hawaiian Islands insular false killer whales showing increase in sample sizes available by cluster from deployments from 2020 through 2022. Deployments from 2007-2019 include one deployment by PIFSC. Cluster designations are based on Mahaffy et al. (in review).

Cluster	# deployments 2007-2019	# 2007-2019 excluding pseudoreplicates	# deployments 2020-2022	Total 2007-2022 excluding pseudoreplicates
1	27	23	4	27
2	6	3	3	5
3	14	10	6	14
4	5	3	3	4
Total	52	39	16	49

Table 7. Prey species documented in the diet of main Hawaiian Islands insular false killer whales, updated from Baird et al. (2021a, supplemental materials) to include Kanpachi documented as prey in 2021. Data from stomach contents from K. West et al. unpublished, U. Hawaiʻi. Photographic data from Baird et al. (2008), Baird (2016), and unpublished data.

English name	**Hawaiian name**	**Scientific name**	**Type of evidence**
Yellowfin tuna	Ahi	*Thunnus albacares*	Photos, stomach
Bigeye tuna	ʻAhi poʻonui	*Thunnus obesus*	Photos
Albacore tuna	ʻAhi palaha	*Thunnus alalunga*	Photos
Skipjack tuna	Aku	*Katsuwonus pelamis*	Photos
Scrawled file fish	Loulu or Oilepa	*Aluterus scriptus*	Photos
Broadbill swordfish	Aʻu ku	*Xiphias gladius*	Photos, stomach
Dolphin fish	Mahimahi	*Coryphaena hippurus*	Photos, stomach
Wahoo	Ono	*Acanthocybium solandri*	Photos
Lustrous pomfret	Monchong	*Eumegistus illustrus*	Photos
Opah		*Lampris guttatus*	Photos, stomach
Threadfin jack	Kagami ulua	*Carangoides otrynter*	Photos
Blue-green snapper	Uku	*Aprion virescens*	Photos
Milkfish	Awa	*Chanos chanos*	Photos
Amberjack	Kāhala	*Seriola quinqueradiata*	Photos
Almaco Jack	Kanpachi	*Seriola rivoliana*	Photos
Giant trevally	Ulua aukea	*Caranx ignobilis*	Photos
Unidentified jack		*Caranx sp.*	Stomach
Shortbill spearfish	Aʻu	*Tetrapterus angustirostris*	Stomach
Bonefish	Oio	*Albula spp.*	Photos, stomach
Diamondback squid		*Thysanoteuthis rhombus*	Stomach
Purpleback flying squid		*Sthenoteuthis oualaniensis*	Stomach

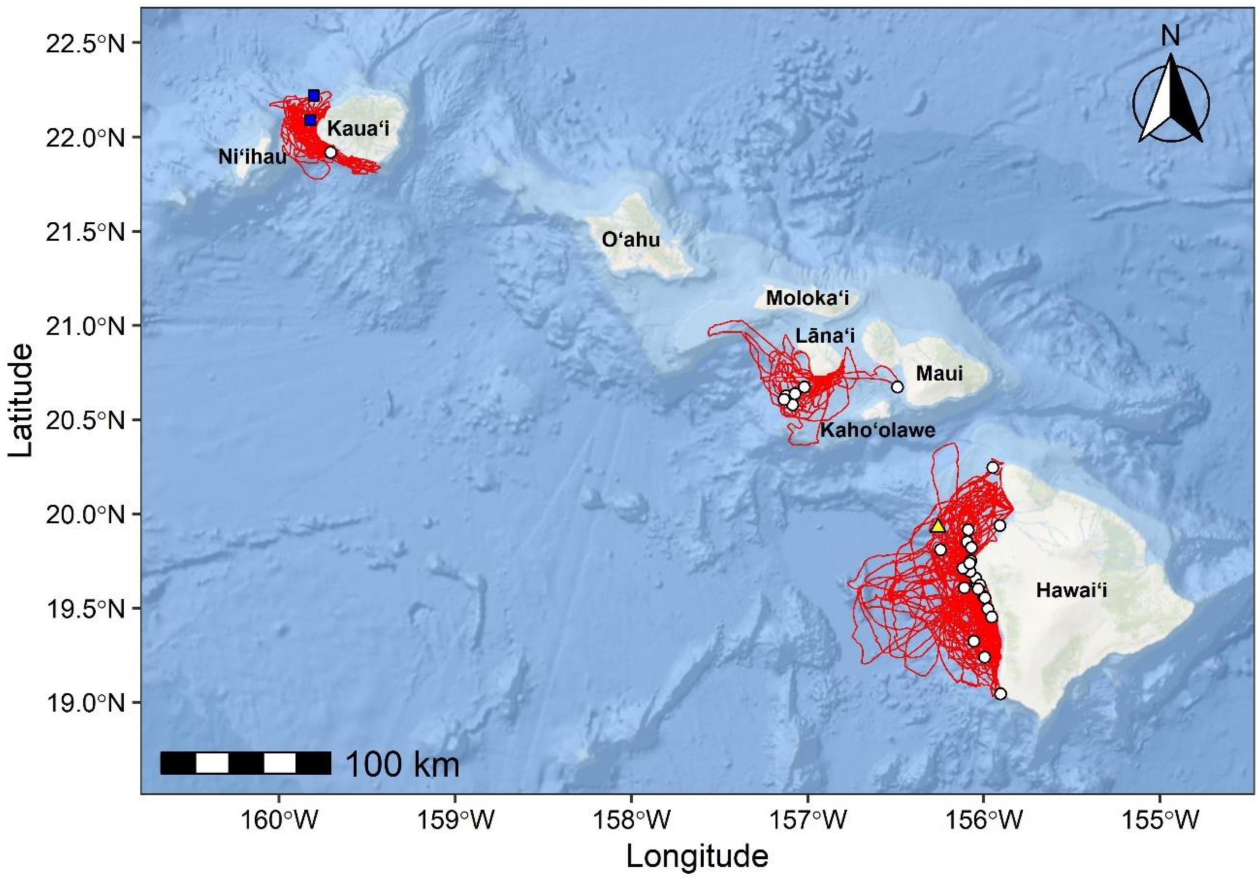

Figure 1. Map showing all CRC search effort (lines) from 2020 through 2022, with population identity of false killer whale sightings indicated by symbol (blue squares – northwestern Hawaiian Islands population' yellow triangle – pelagic population; white circles – main Hawaiian Islands insular population).

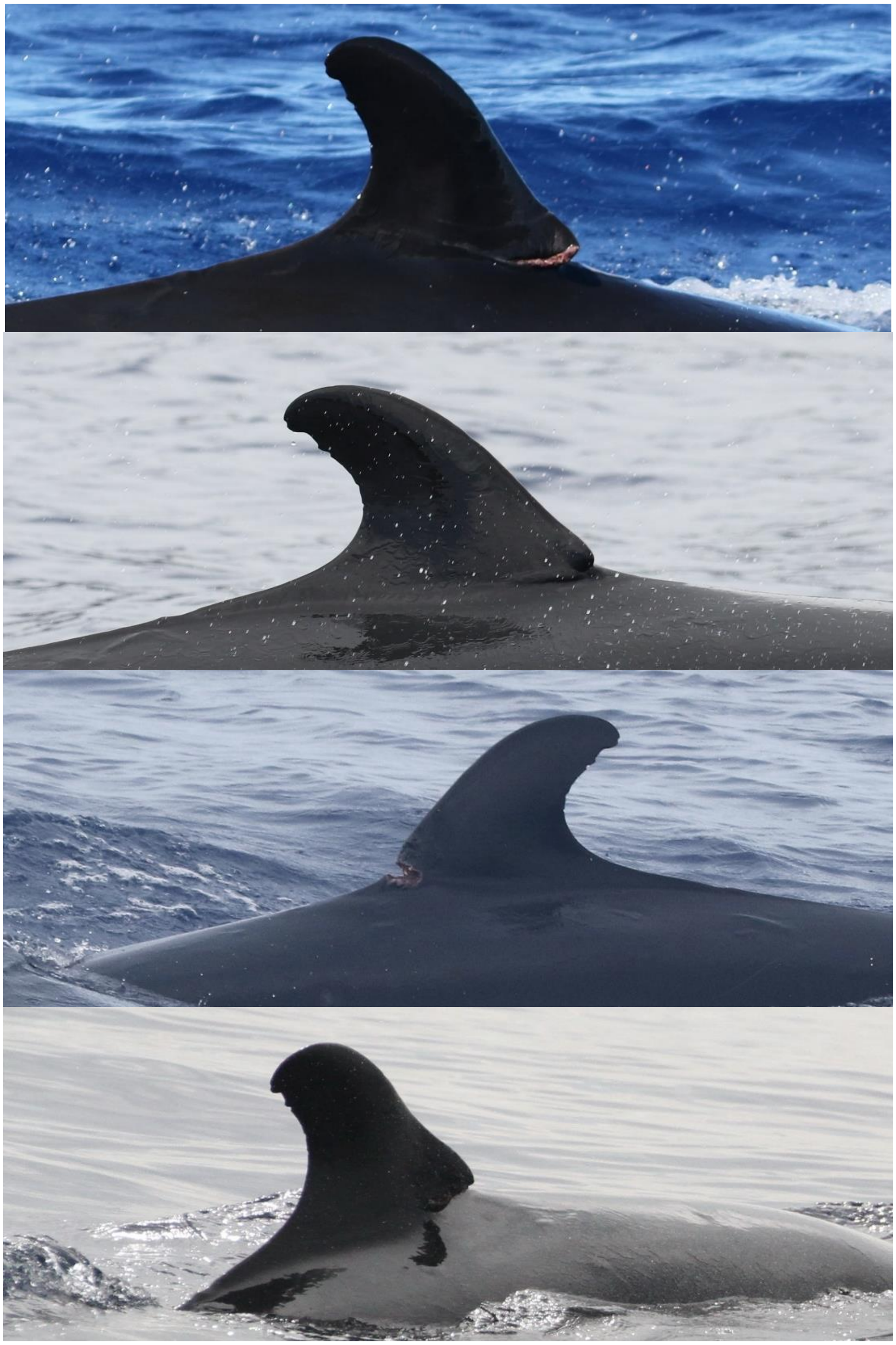

Figure 2. False killer whale HIPc310. Top – when fresh injury was first documented on 8 October 2016 (photo by RW Baird). Second – on 5 September 2021 showing completely healed area (photo by CJ Cornforth). Third and fourth – from 16 November 2021 with fresh re-injury to leading edge of fin, showing the bend of the leading edge of the fin to the right (photos from Wild Side Specialty Tours).

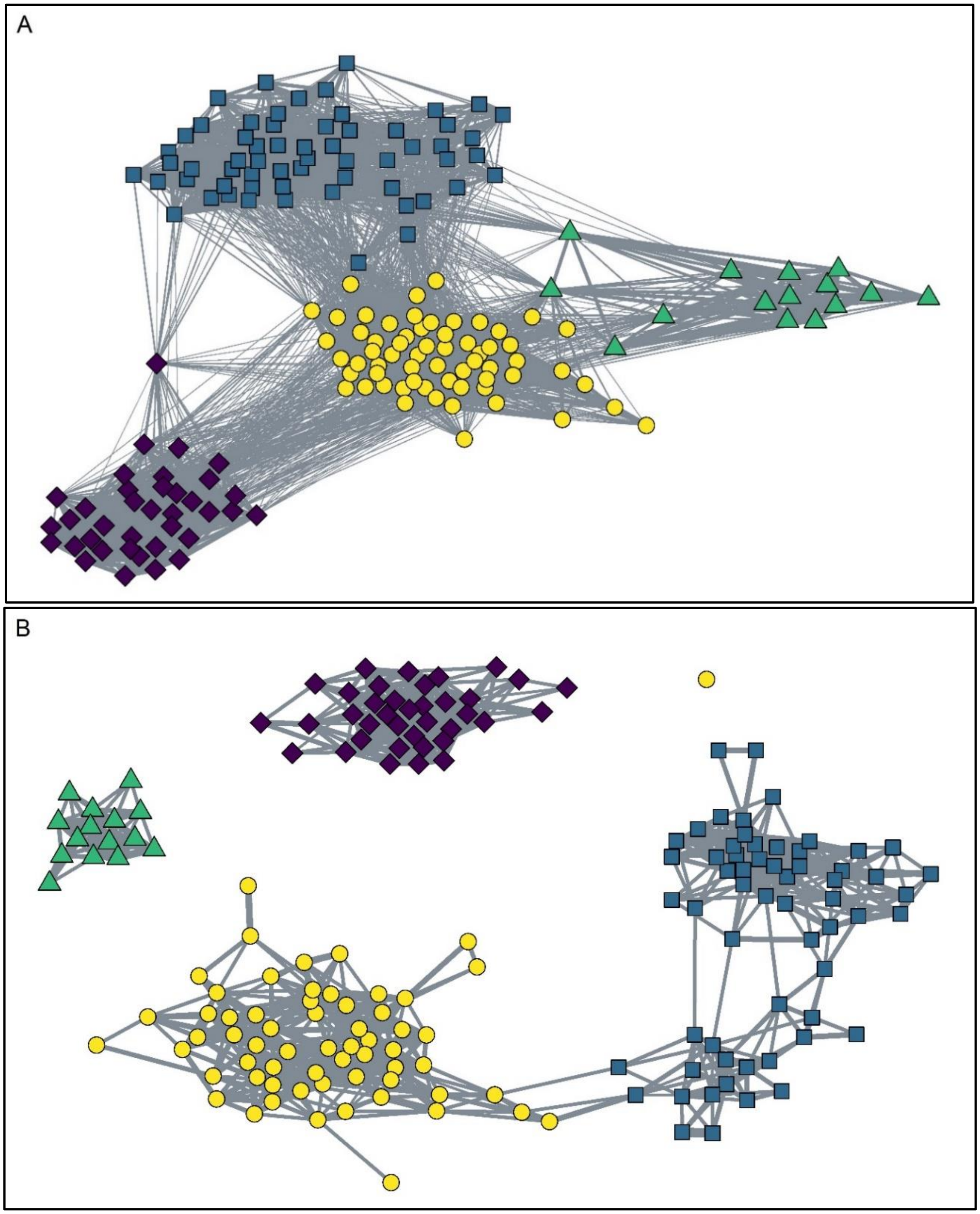

Figure 3. Weighted social network diagrams generated using the Louvain algorithm* with node color and shape indicating social clusters: Cluster 1 = yellow circles, Cluster 2 = green triangles, Cluster 3 (including individuals previously considered part of Cluster 5) = blue squares, Cluster 4 = purple diamonds. A: All individuals (1999-2021) considered slightly distinctive or above with fair or better quality photos sampled on five or more days for all associations (i.e., the restricted dataset). B: associations with a half-weight index ≥ 0.3. *Fastgreedy and Walktrap algorithms produced identical cluster assignments. From Mahaffy et al. (in review).

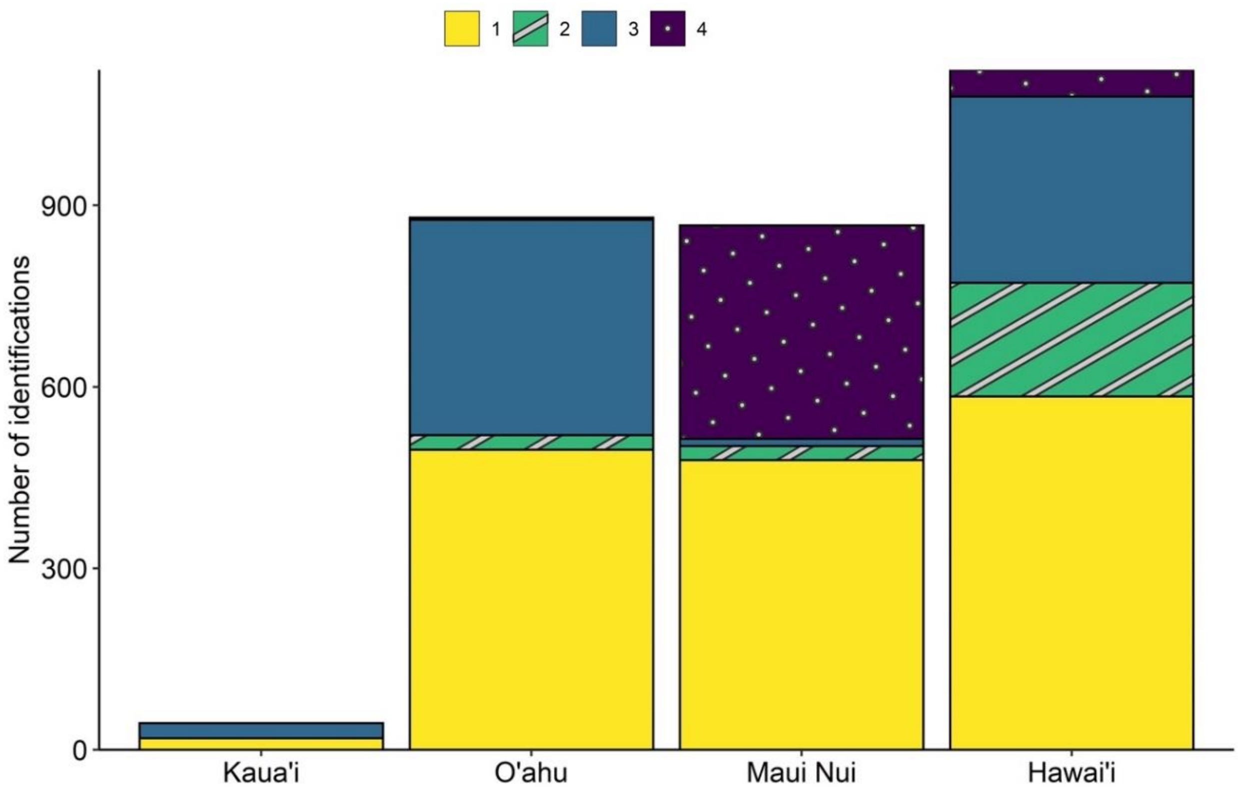

Figure 4. Breakdown of identifications of each social cluster by island area for clusters identified with the Louvain algorithm for photo-identification data available from 1999 through 2021, from Mahaffy et al. (in review). This includes individuals that were slightly distinctive or greater with fair or better-quality photos. Clusters are coded by color and texture (see key at top).

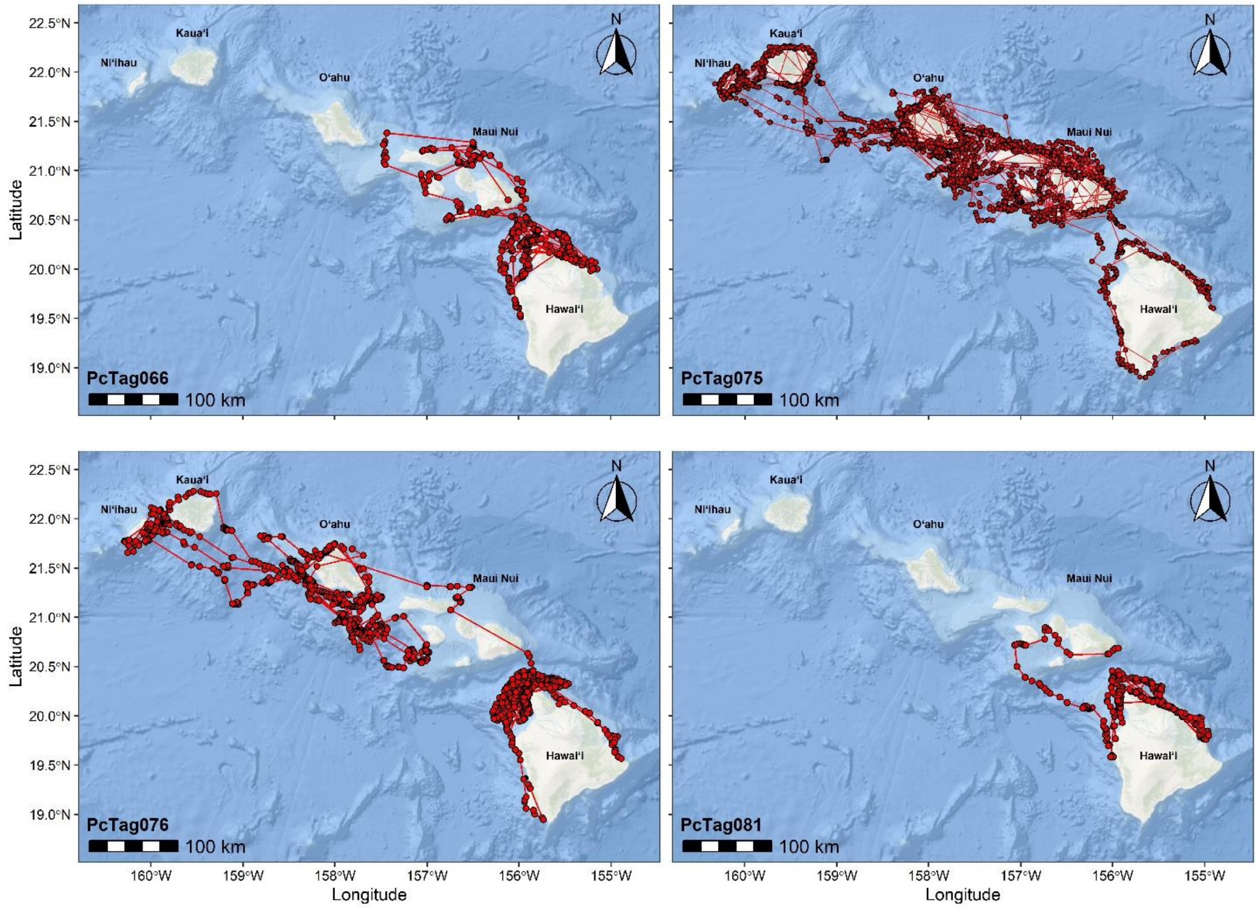

Figure 5. Maps of Cluster 1 individuals tagged between 2020 and 2022. All were tagged off Hawai‘i Island. Top left. PcTag066 tagged 22 June 2020 and tracked for 28 days. Top right. PcTag075 tagged 5 September 2021 and tracked for 188 days. Bottom left. PcTag076 tagged 15 September 2021 and tracked for 57 days. Bottom right. PcTag081 tagged 7 July 2022 and tracked for 13 days.

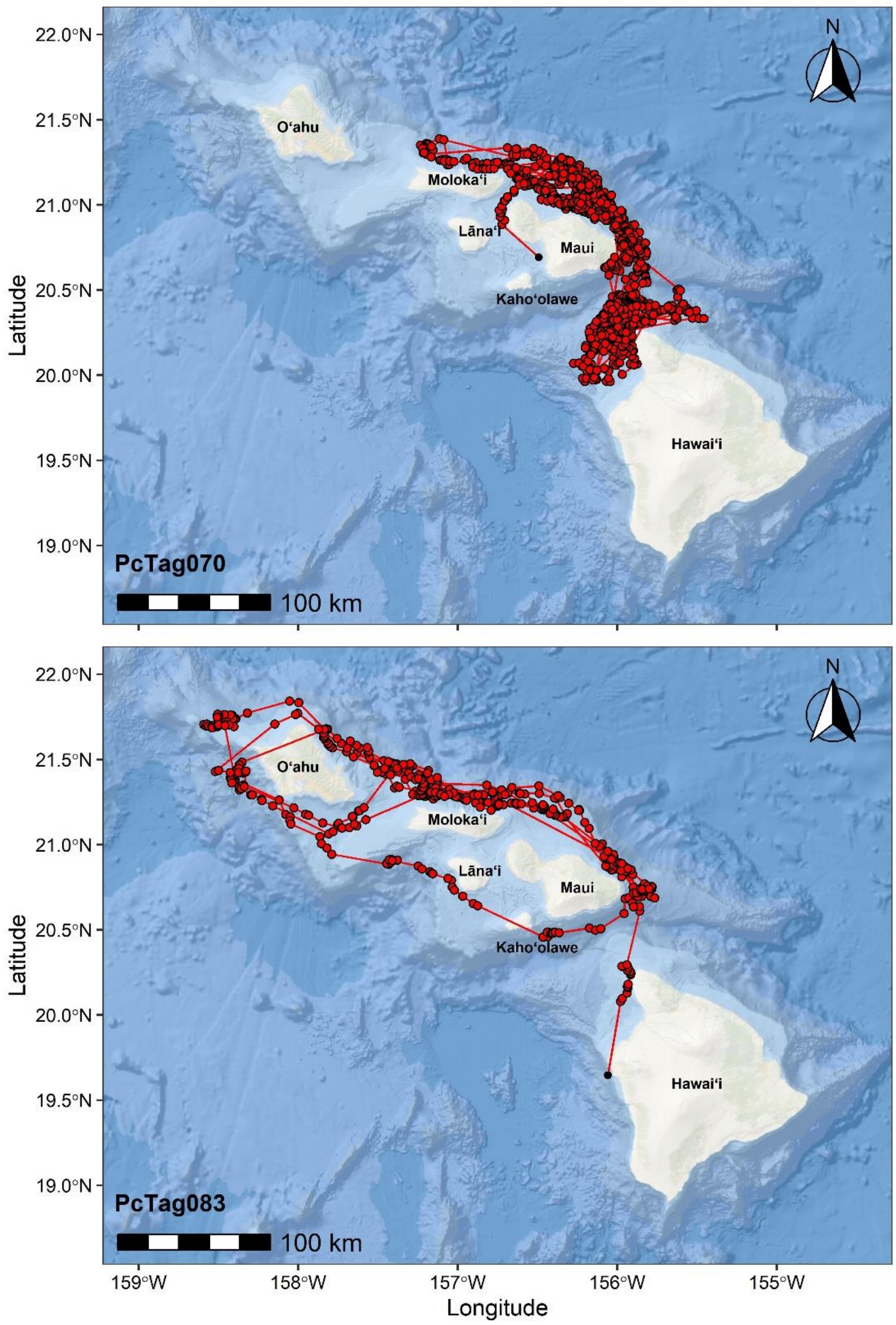

Figure 6. Maps of two Cluster 2 individuals tagged between 2020 and 2022. Top. PcTag070 tagged off Maui 7 December 2020 and tracked for 42 days. Bottom. PcTag083 tagged off Hawaiʻi Island 13 November 2022 and tracked for 22 days. Note, PcTag082, also from Cluster 2, was tagged 13 November 2022 but is still transmitting as of February 7, 2023.

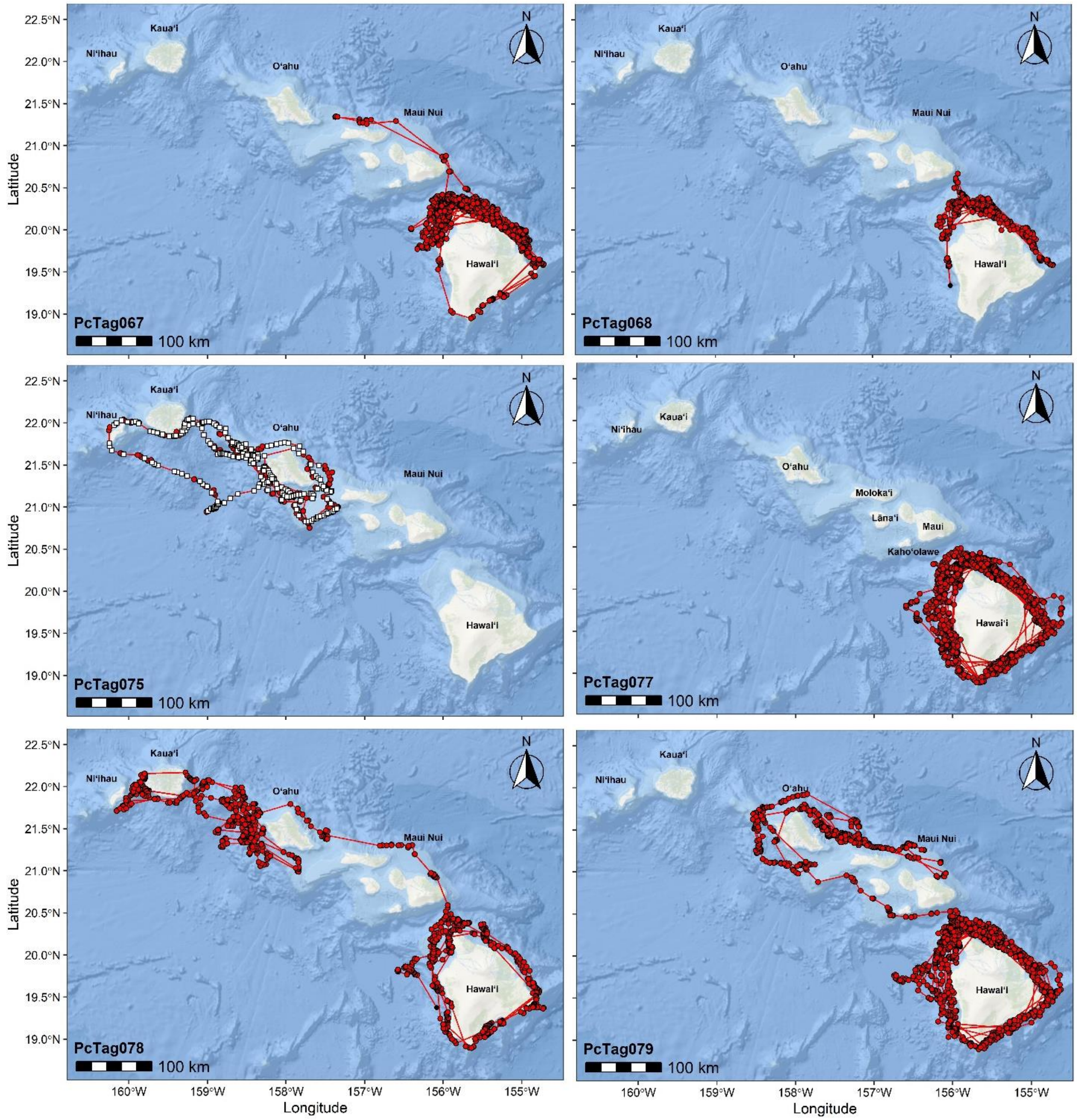

Figure 7. Maps of six Cluster 3 individuals tagged between 2020 and 2022. All were tagged off Hawai'i Island except PcTag074. Top left. PcTag067 tagged 29 September 2020 and tracked over 81 days. Top right. PcTag068 tagged 19 October 2020 and tracked over 21 days. Middle left. PcTag074 tagged off Kaua'i 8 August 2021 and tracked over 12 days. Fastloc®-GPS locations are shown as white circles. Middle right. PcTag077 tagged 30 September 2021 and tracked over 68 days. Bottom left. PcTag078 tagged 15 October 2021 and tracked for 44 days. Bottom right. PcTag079 tagged 11 November 2021 and tracked for 77 days. Despite the overlapping time frame, PcTag077 remained entirely around Hawai'i Island over the 68-day period, while PcTag078 ranged throughout the entire known population range over 44 days.

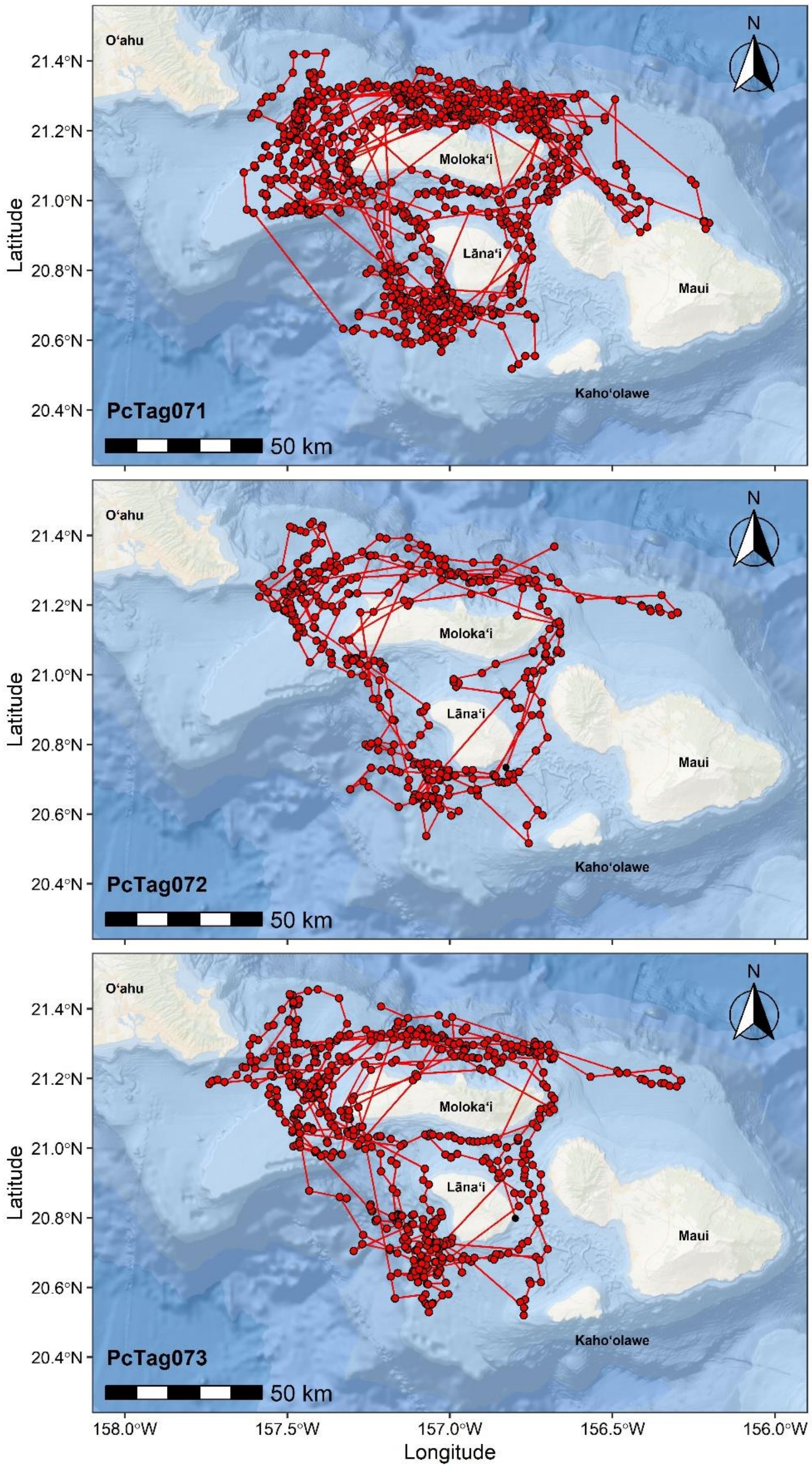

Figure 8. Maps of three Cluster 4 individuals tagged between 2020 and 2022. All three were tagged off Lāna'i during the December 2020 field effort. Top. PcTag071 tracked for 40 days. Middle. PcTag072 tracked for 18 days. Bottom. PcTag073 tracked for 24 days.

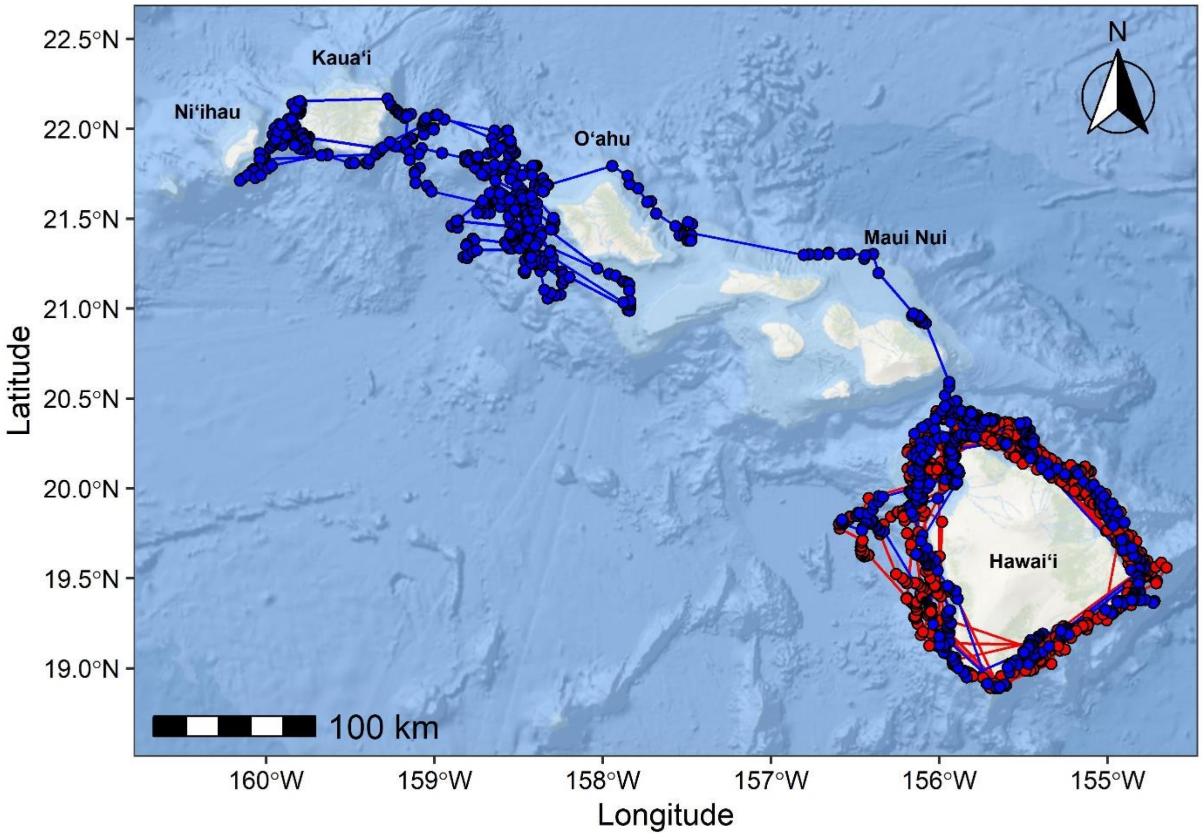

Figure 9. Map of tag data from PcTag077 (red) and PcTag078 (blue), both members of Cluster 3, during the period of overlap between transmissions from the two tags. This map shows data from 15 October 2021 through 29 November 2021. PcTag078 remained associated with PcTag077 around Hawai'i Island for the first 18 days of this period (through 2 November 2021) before moving to the northwest, while PcTag077 remained around Hawai'i Island for the entire period.

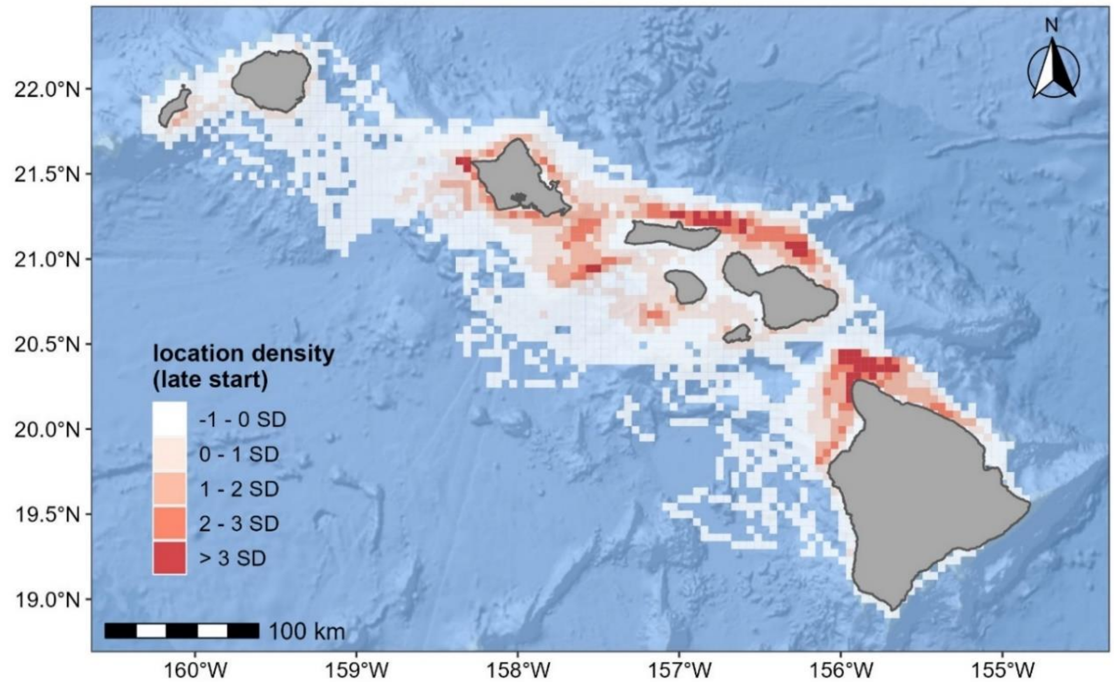

Figure 10. Density map for false killer whales from Cluster 1 of the MHI insular population, using all tag data available through 2022 after controlling for pseudoreplication.

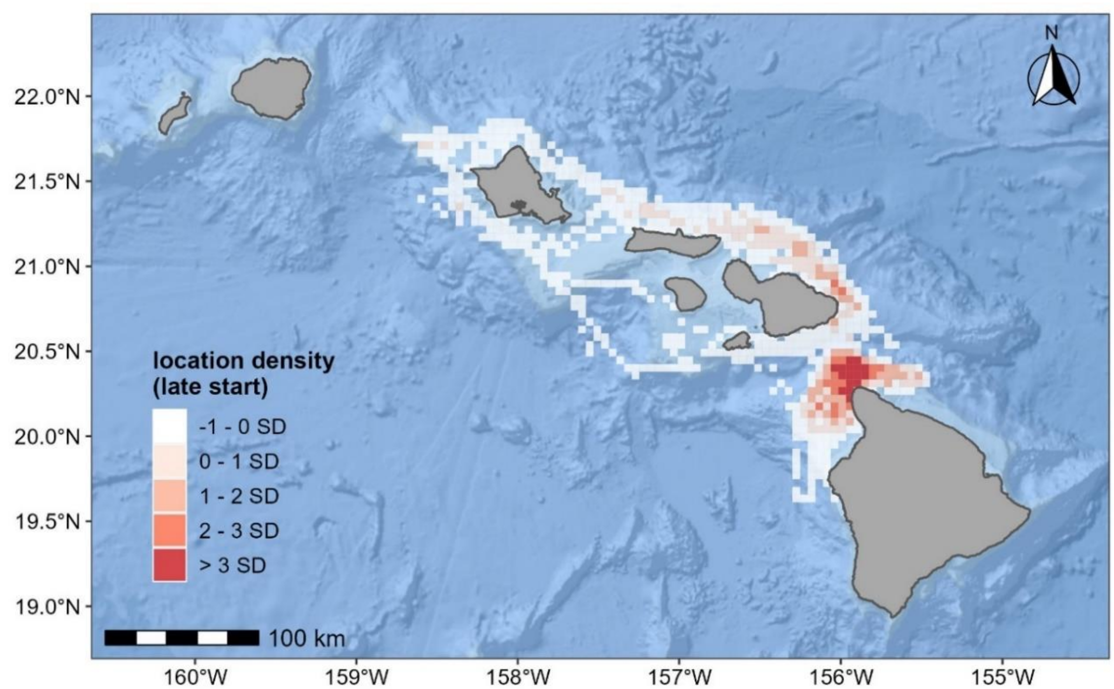

Figure 11. Density map for false killer whales from Cluster 2 of the MHI insular population, using all tag data available through 2022 after controlling for pseudoreplication. PcTag082, tagged in November 2022 and still transmitting as of February 7, 2023, is not included.

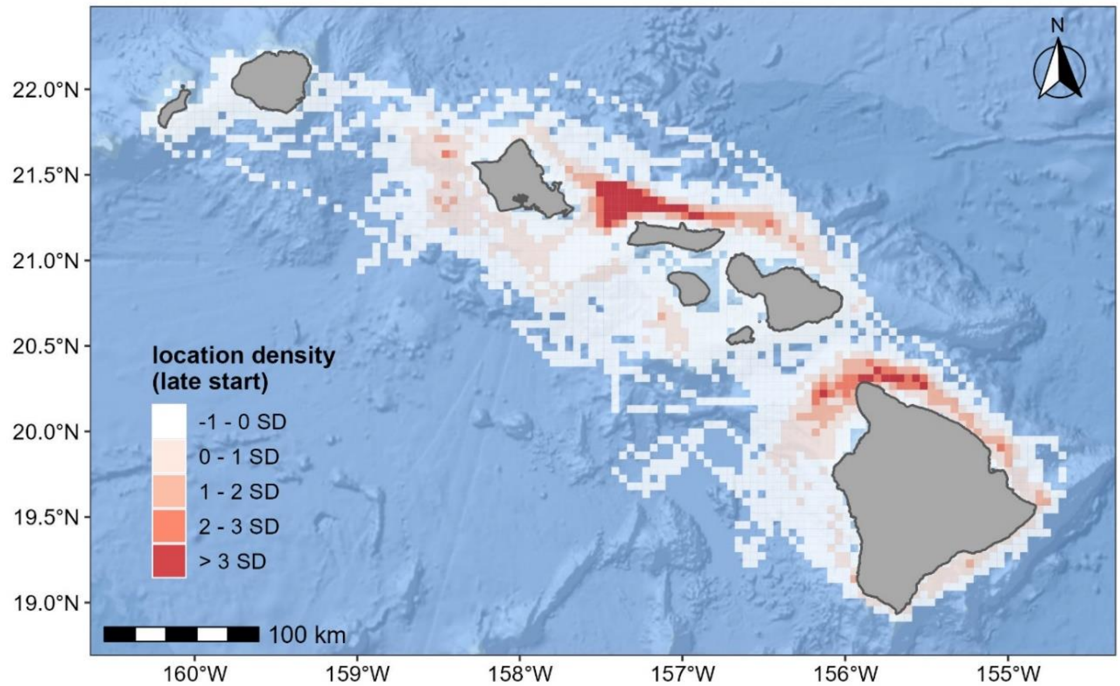

Figure 12. Density map for false killer whales from Cluster 3 of the MHI insular population, using all tag data available through 2022 after controlling for pseudoreplication.

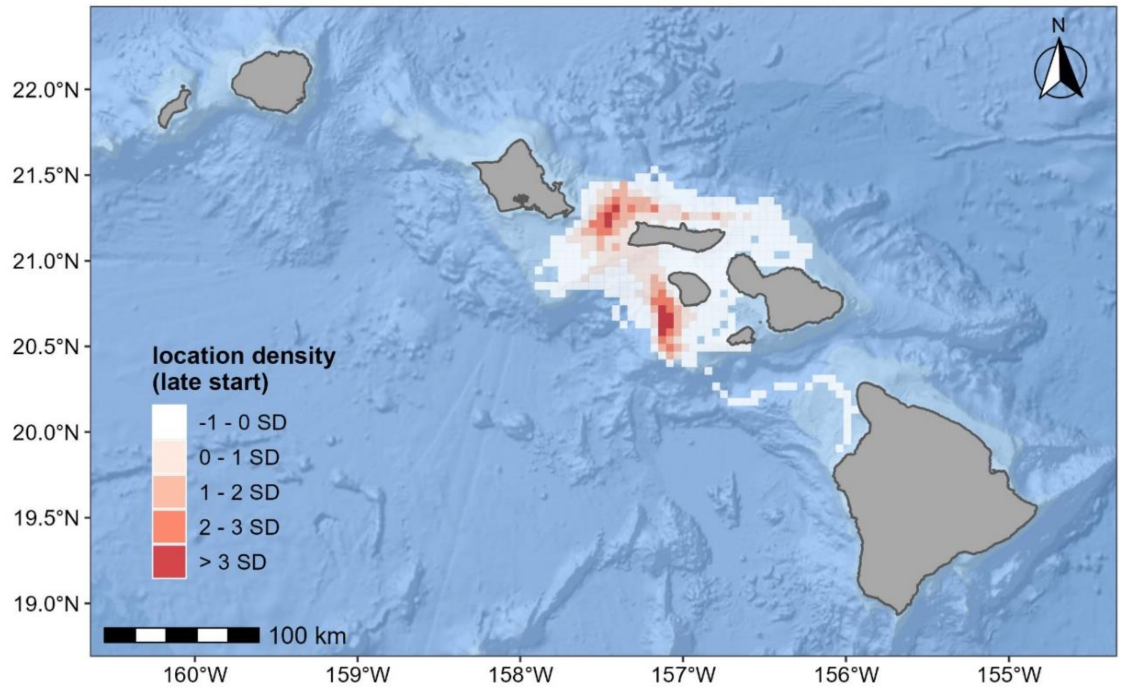

Figure 13. Density map for false killer whales from Cluster 4 of the MHI insular population, using all tag data available through 2022 after controlling for pseudoreplication.

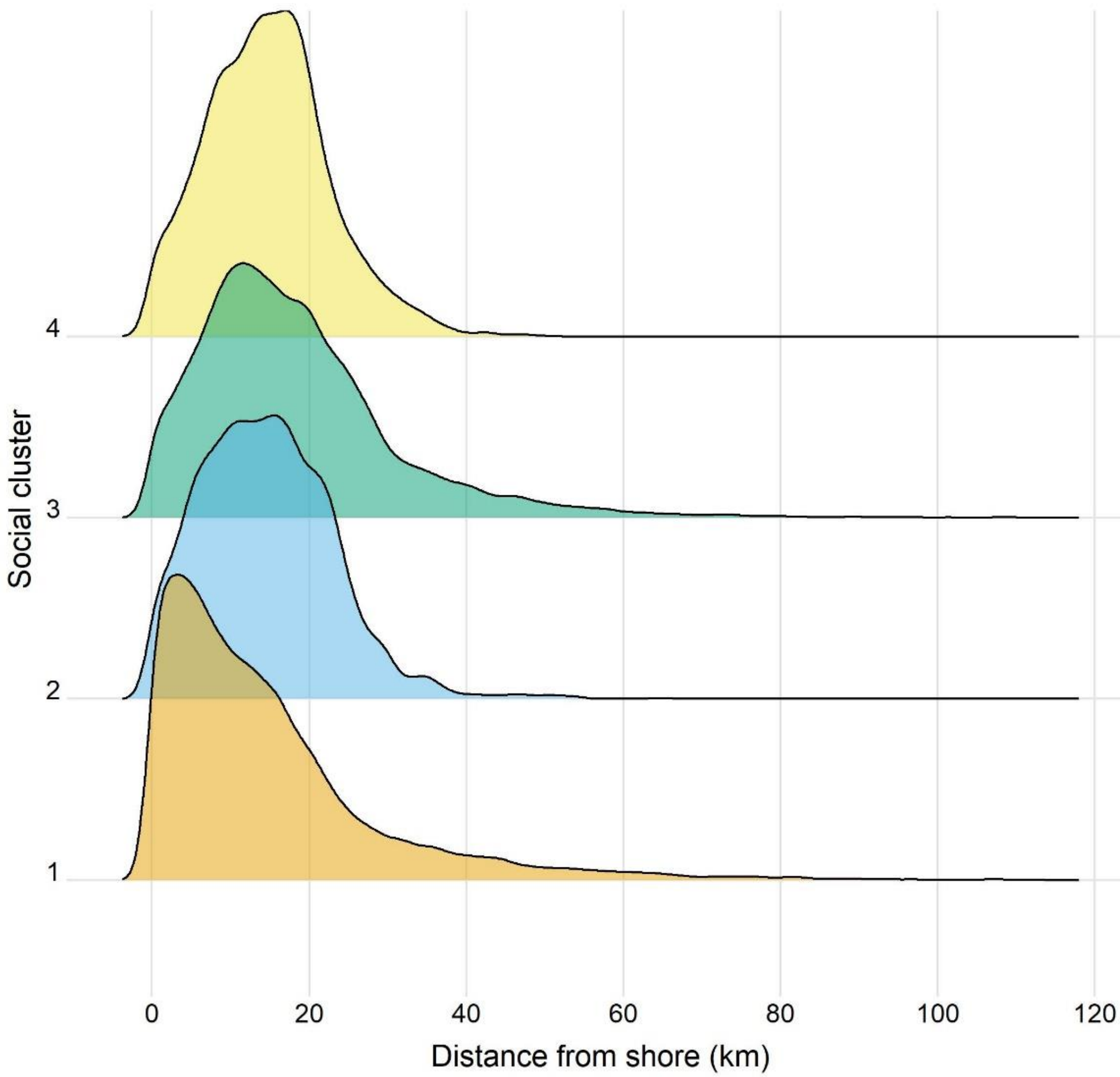

Figure 14. Distributions of distance from shore values for hourly satellite tag locations (see methods for details on processing) among the four social clusters.

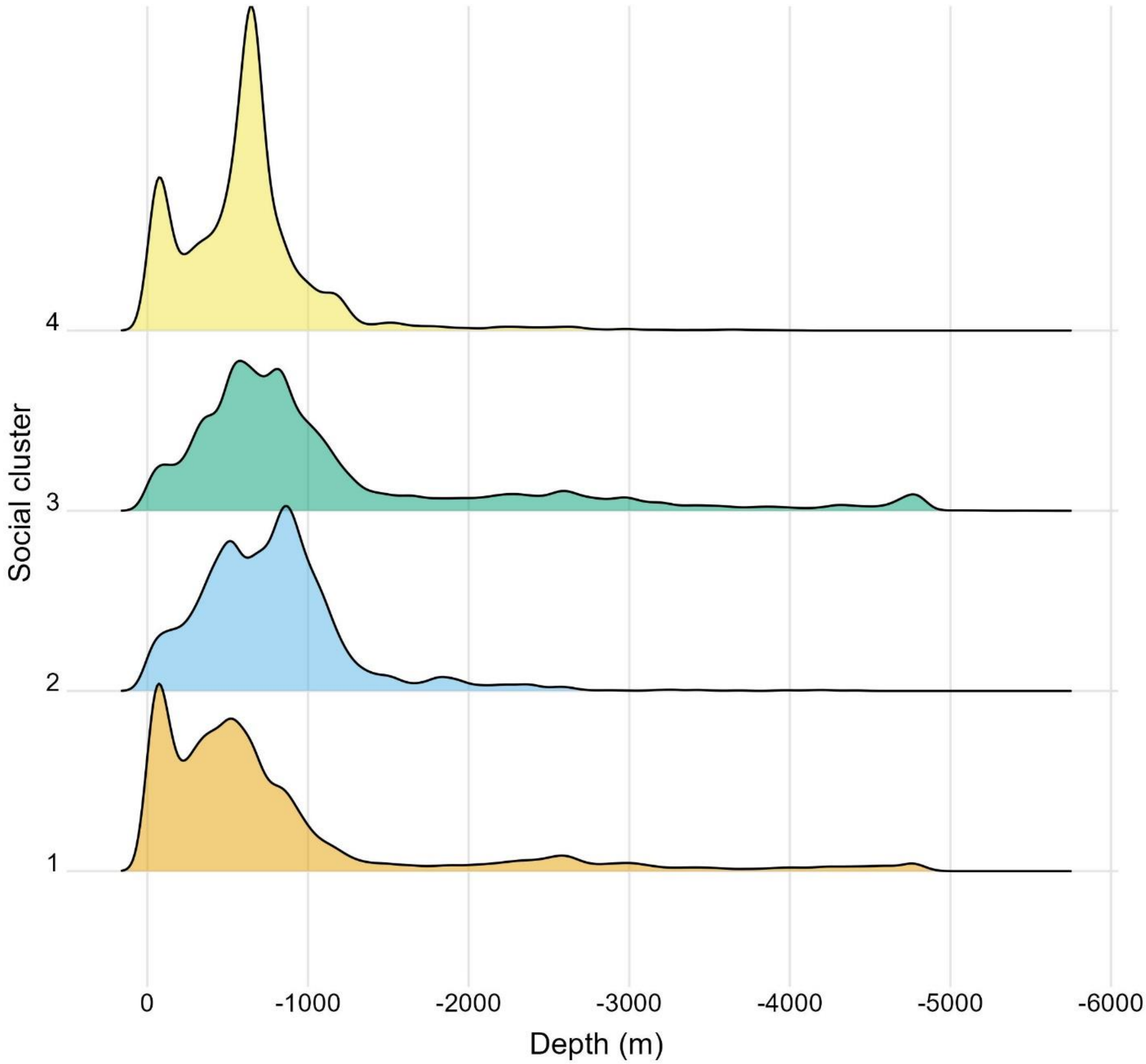

Figure 15. Distributions of seafloor depth values for hourly satellite tag locations (see methods for details on processing) among the four social clusters.

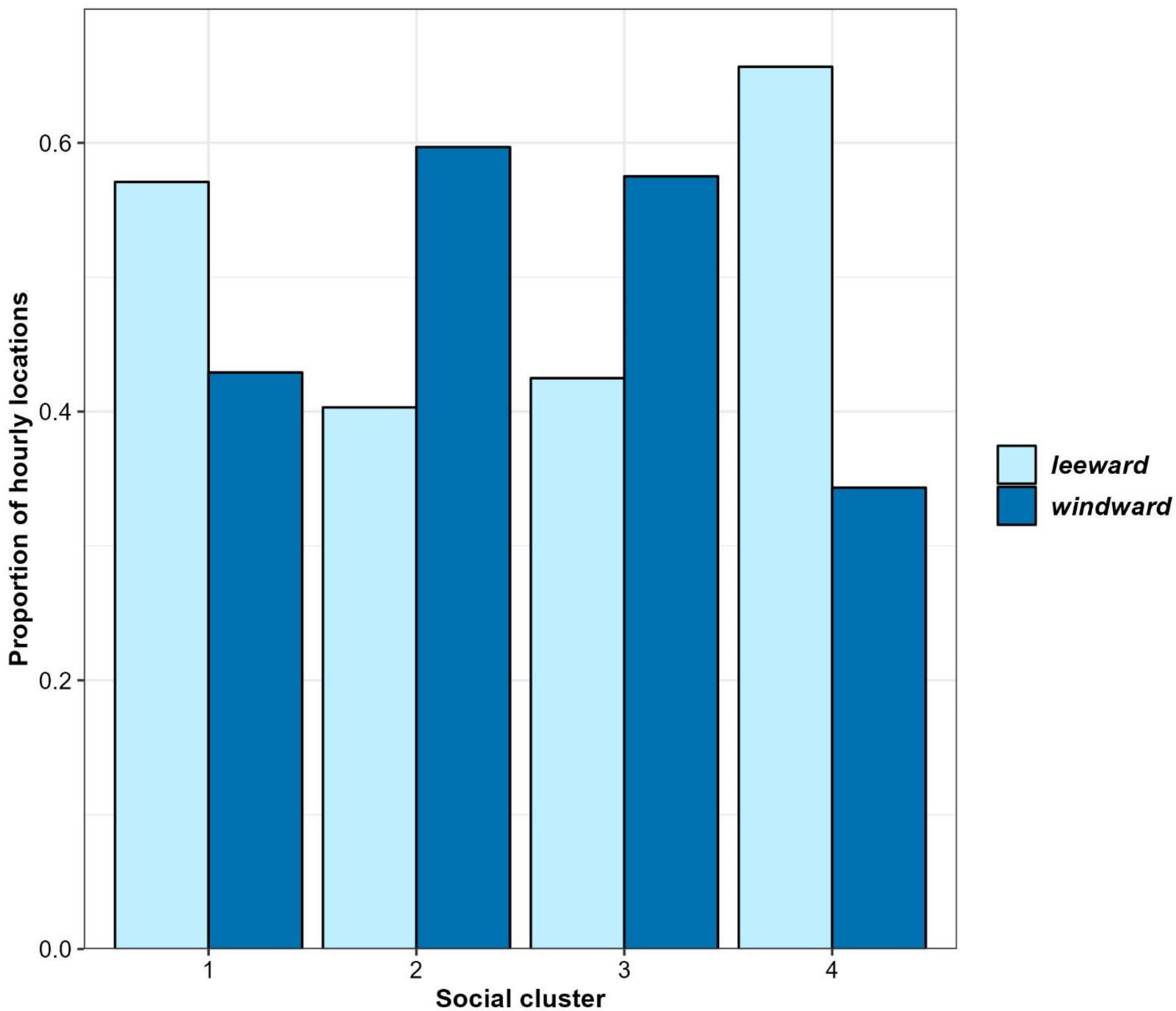

Figure 16. Proportion of hourly locations (see methods for details on satellite tag data processing) occurring on leeward and windward sides of the islands among the four social clusters.