

# **Abundance of short-finned pilot whales near Kaua‘i Island, Hawai‘i**

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## ABSTRACT

Accurate stock assessments that reflect true population structure are essential for effective marine mammal conservation under the U.S. Marine Mammal Protection Act. Current abundance estimates for short-finned pilot whales (*Globicephala macrorhynchus*) in Hawai‘i group all individuals together, potentially obscuring declines in smaller, demographically independent populations (DIPs). Whales associated with Kaua‘i and Ni‘ihau are of particular concern due to their limited ranges and high exposure to anthropogenic noise. To generate population-specific abundance estimates, spatial capture-recapture models were applied to long-term photo-identification data collected by Cascadia Research Collective between 2011 and 2023. Surveys followed non-systematic boat tracklines, identifying 237 distinct individuals, including both island-associated and pelagic whales. Spatial encounter histories were built using a  $4 \times 4$  km grid and analyzed with a spatial capture-recapture modeling approach. Models incorporated depth, distance to shore, time, and population structure as covariates. Top-ranked models included study period effects on density and detection, with detection probability showing a quadratic relationship with depth, indicating strong habitat influences. Mean densities across two-year periods were 2.5 and 2.2 marked whales per 100 km<sup>2</sup> for island-associated and pelagic populations, respectively. When scaled to total abundance, these corresponded to mean population sizes of 587 (SD  $\pm$  494) and 446 (SD  $\pm$  430) individuals. Detection probability peaked along the 1,500-3,000 m depth contour, consistent with known foraging habitats. These findings provide the first spatially explicit, population-level abundance estimates for short-finned pilot whales near Kaua‘i and Ni‘ihau, offering a framework for monitoring localized population trends and demonstrating how non-systematic survey data can inform marine mammal management and conservation.

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## 1. Introduction

The U.S. Marine Mammal Protection Act (MMPA), enacted in 1972, provides the legal framework for conserving and managing marine mammal populations within U.S. waters. Under this legislation, National Oceanic and Atmospheric Administration (NOAA) is tasked with conducting stock assessments, i.e., comprehensive population evaluations, for each marine mammal population. These assessments are fundamental for identifying population trends, assessing threats, and guiding management actions to protect vulnerable species. Abundance estimates derived from these assessments inform key management metrics such as Potential Biological Removal levels (PBR; Wade, 1998) and are central to fulfilling the MMPA's conservation objectives. With 261 stocks managed by NOAA in U.S. waters, these metrics help prioritize conservation efforts. If estimated mortality or serious injuries exceed PBR, or if abundance estimates show a decline, management actions may be triggered, such as establishing a Take Reduction Team which brings together diverse stakeholders to develop strategies for mitigating marine mammal losses. By continuously monitoring these metrics, managers can attempt to mitigate population decline and support the recovery of at-risk stocks.

The short-finned pilot whale (*Globicephala macrorhynchus*), one of the species assessed under the MMPA, occurs throughout tropical and subtropical waters, including around the Hawaiian Islands. Pilot whales are recognized for their deep-dives, often reaching depths of up to 800 meters to hunt prey in the deep-scattering layer (Baird et al., 2003; Gough et al., 2025). Known for their social nature, short-finned pilot whales in Hawai'i typically form social units of  $10.44 \pm 3.75$  individuals, that merge with other units to create clusters of  $23.25 \pm 7.8$  individuals (Mahaffy et al., 2015). These clusters form distinct communities defined by their geographic ranges, association patterns and habitat use patterns around the Hawaiian Islands (Mahaffy et al., 2015;

Baird et al. 2013; Kratofil et al. 2023). For example, photo-identification surveys conducted between 2003-2007 around the main Hawaiian Islands indicate the presence of an insular population with island-associated communities, as well as a distinct pelagic population (Mahaffy et al., 2015). Telemetry data supports this population structure, with some tagged individuals exhibiting island residency while others move extensively throughout the archipelago (Baird, 2016; Kratofil et al. 2023). Genetic studies corroborate these findings, indicating at least two distinct populations: one associated with the main Hawaiian Islands (MHI) and another pelagic stock, with evidence of both western and eastern communities within the MHI population (Van Cise et al., 2017).

NOAA's 2017 estimate of 7,956 short-finned pilot whales total in Hawaiian waters (CV = 0.59; Bradford et al., 2021) does not differentiate between island-associated communities and pelagic populations. Failing to account for population structure risks masking declines in smaller, demographically independent populations (DIPs), which are sustained by internal recruitment rather than immigration or emigration (Martien et al., 2019). This can result in overly optimistic assessments and insufficient protections for vulnerable groups. Thus, refining stock assessments by estimating abundance separately for each grouping, particularly the island-associated groups, would benefit management (Taylor, 1997). Evidence from multiple sources suggests that island-associated pilot whale communities in Hawai'i function as DIPs (Mahaffy et al., 2015; Kratofil et al. 2023; Van Cise et al., 2017). Such population structuring is common among marine mammals (e.g., Servidio et al., 2019; Restrepo Garzón, 2022; Alves et al., 2013), including rough-toothed dolphins (*Steno bredanensis*), spinner dolphins (*Stenella longirostris*), and melon-headed whales (*Peponocephala electra*) in Hawai'i (Albertson et al., 2016; Andrews et al., 2010; Aschettino et al. 2012).

Island-associated pilot whales are particularly vulnerable to localized threats because DIPs exist largely in isolation; consequently, stressors affecting a single population may cause significant depletion of that DIP while others remain unaffected. In the case of pilot whales in Hawai‘i, commercial and recreational fishing activities can lead to entanglements and mortality (Baird, 2016; Carretta et al., 2020; Bradford & Forney, 2014), while in some species anthropogenic noise has been linked to hearing loss, behavioral disruption, increased energy expenditure, and mass stranding events (McCarthy et al., 2011; Czapanskiy et al., 2021; Bhagarathi et al., 2024; Parsons, 2017). These strandings are often exacerbated by the species’ strong social cohesion, where the loss or disturbance of a single individual can impact the entire group (Mazzuca et al., 1999; Wade et al., 2012). One notable source of concern is the Rim of the Pacific (RIMPAC) naval exercise, the largest international maritime exercise in the world, which is held biennially in Hawaiian waters. RIMPAC involves extensive military activity, including the use of mid-frequency active sonar, a known stressor for deep-diving cetaceans that have been linked to mass strandings (Southall et al., 2006; Baird, 2016; Bradford & Lyman, 2018).

In addition to widespread naval exercises like RIMPAC, island-associated pilot whales off Kaua‘i and Ni‘ihau may face elevated risk from more localized sources of sonar, particularly due to the presence of the Pacific Missile Range Facility (PMRF) off Kaua‘i’s leeward coast. These whales face a markedly different threat exposure than their offshore counterparts. For example, telemetry data indicate that island-associated pilot whales spend about 29% of their time within the vicinity of the PMRF, while offshore individuals spend less than 1% of their time in this area (Kratofil et al., 2023; Baird et al., 2017). Such differential sonar exposure between distinct populations potentially leads to varying impacts on their population dynamics. As such, improving abundance estimates for each DIP has important management consequences.

For this study, spatial capture-recapture methods were used to estimate the abundance of both all short-finned pilot whales near Kaua‘i and Ni‘ihau and the island-associated subset of the western community. Island-associated communities have been challenging to study since the line-transect surveys conducted by NOAA’s Pacific Islands Fisheries Science Center (PIFSC), which inform many stock assessments, largely occur outside the insular populations’ ranges. Consequently, small boat surveys launched from shore may provide a more effective approach for monitoring these populations.

Since 2003, Cascadia Research Collective (CRC) has conducted boat-based surveys following a non-systematic survey design, which offers a more cost-effective and logistically practical alternative to data collection for rare and highly mobile cetacean species that often lack sufficient funding for dedicated survey methods (Boys et al., 2019; Baird et al., 2024). Non-systematic survey designs, however, can produce biased estimates of abundance, potentially misleading management (Badger et al., 2024; Hammond et al., 2021; Marsh & Sinclair, 1989). To address this, pilot whale abundance was estimated with spatial capture-recapture (SCR), an extension of traditional capture-recapture methods that incorporate spatial information typically ignored in standard approaches (Efford 2004). SCR has proven an effective method for non-systematic surveys as it models the spatial distribution of encounters and accounts for uneven sampling effort across the study area, making it well-suited for addressing the biases inherent in non-systematic survey data (Thompson et al., 2012; Russel et al., 2012). By integrating long-term photo-identification datasets (2011 to 2023) with SCR methods, this study aims to generate robust, spatially explicit abundance estimates to support community-specific assessments.

The objectives of this study were to: (a) estimate the abundance of short-finned pilot whales in waters near Kaua‘i and Ni‘ihau from 2011 to 2023; (b) estimate the abundance of the western

community subset utilizing these islands; and (c) evaluate temporal trends in abundance for both the broader population and the island-associated community. Given the greater overlap of the island-associated whales with the PMRF, understanding their abundance trends is especially important for evaluating potential impacts of naval activity. This study not only improves abundance estimates critical for marine mammal management and mitigation of localized threats, particularly military activities, but also demonstrates how non-systematic survey data can be leveraged using SCR methods to yield valuable insights into the ecology of poorly understood cetacean populations.

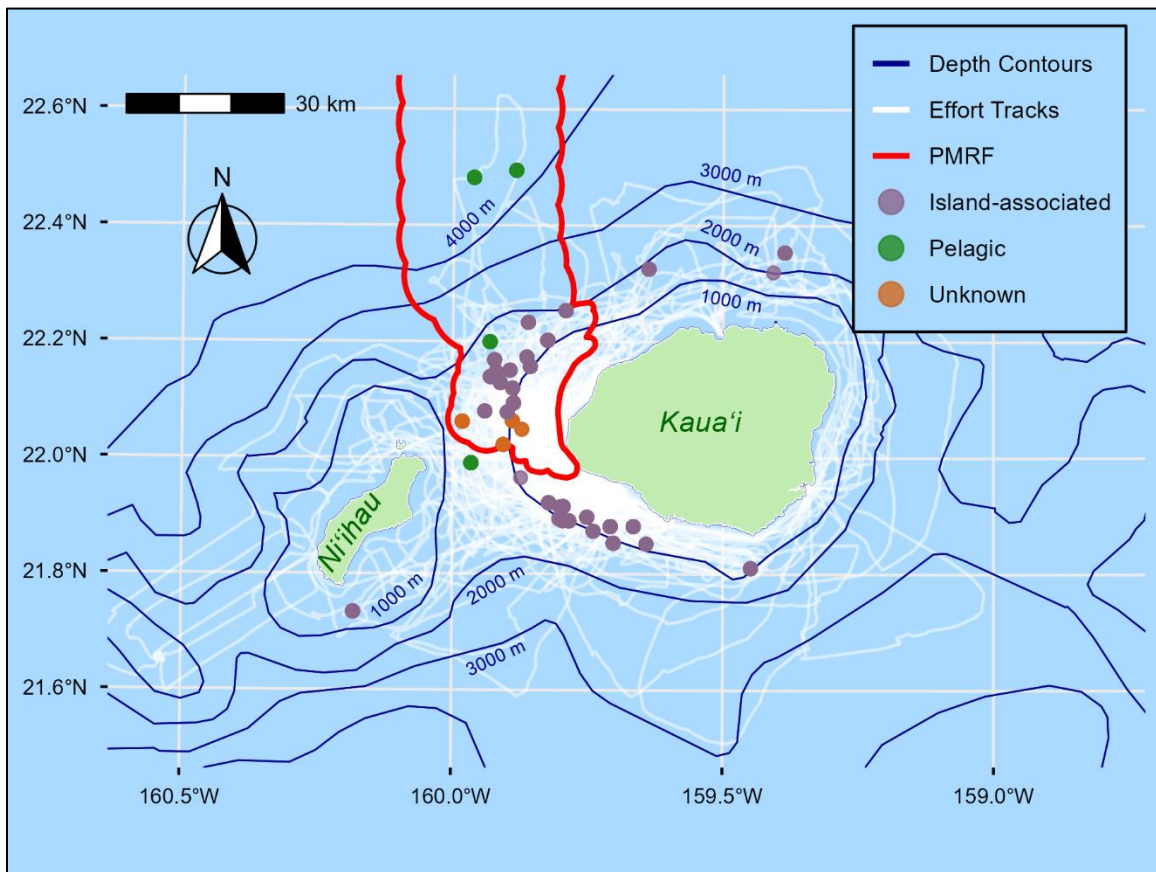
## **2. Methods**

Abundance estimates were based on small-boat surveys near Kaua‘i and Ni‘ihau, where photo-identification and satellite telemetry provided complementary data on pilot whale individuals, occurrence and movements (Figure 1). Processed photographs were used to identify distinctive individuals and build encounter histories, which formed the basis for spatially explicit capture-recapture models incorporating survey effort, habitat covariates, and population structure.

### *2.1 Data collection*

CRC conducted small-boat surveys for cetaceans during dedicated field efforts lasting one to two weeks off Kaua‘i and Ni‘ihau from 2011 to 2023 (excluding 2019). Surveys were designed to maximize cetacean encounters and spatial coverage near Kaua‘i and Ni‘ihau (Baird et al., 2013, 2024). Each field season was composed of multiple survey days, during which an onboard GPS system logged latitude and longitude at five-minute intervals. When pilot whales were encountered, photo-identification was conducted to capture images of as many individuals as possible, enabling identification based on distinctive dorsal fin markings. In addition to visual

search efforts, some encounters were informed by acoustic detections provided by the Navy and by reports from tour operators in the area (see discussion). These daily survey efforts formed the individual “occasions” in the multi-session, spatial capture–recapture framework (Sutherland, Royle, & Linden, 2018), resulting in encounter histories for distinctive or very distinctive individuals in the waters surrounding Kaua‘i and Ni‘ihau.



**Fig. 1** Survey efforts from 2011 to 2023, representing non-systematic tracklines updated every five minutes (white), sightings color-coded by population (island-associated as purple, pelagic as green, and unknowns as orange), depth contours (dark blue), and the PMRF (red).

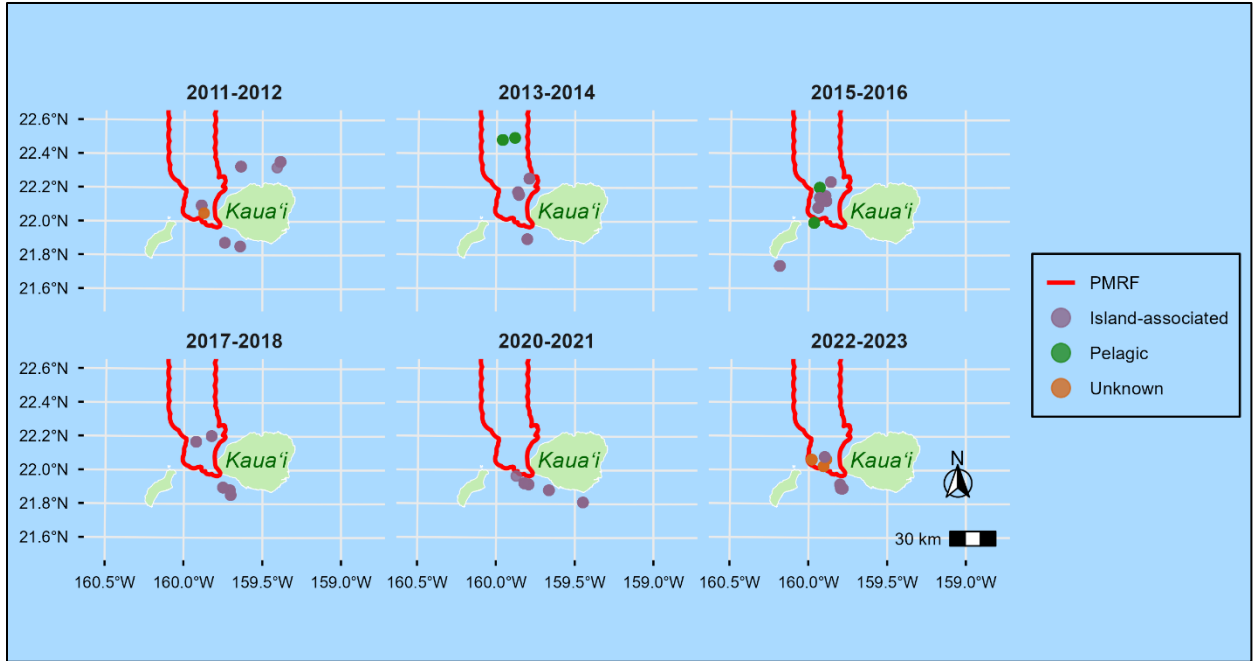
## *2.2 Photo quality assessment and grading of distinctiveness*

Pilot whales were identified by distinct nicks and notches along their dorsal fin (Würsig & Würsig, 1977). A quality assessment scale was used to select photo-identification images for analysis to reduce the likelihood of misidentification (Rosel et al., 2011). Photographs were evaluated on dorsal fin clarity, angle to the photographer, proportion of the fin visible, and the fin's relative size in the frame (Mahaffy et al., 2015). For each individual encountered, the best photograph was assigned a quality score from 1-4. Analyses were restricted to individuals with good or excellent quality (scores 3-4) photos. Individuals were assessed for distinctiveness and classified as “not distinctive,” “slightly distinctive,” “distinctive,” or “very distinctive” (distinctiveness scores 1-4). Individuals rated as not distinctive or slightly distinctive (1 or 2) were excluded from capture-recapture analysis but retained for estimation of the population mark rate used to scale abundance estimates. The mark rate was calculated as the proportion of individuals classified as distinctive or very distinctive relative to the total number of individuals assessed for distinctiveness during encounters. Individuals were matched between encounters based on fin shape, number, size, shape, and relative positioning of dorsal fin notches, and occasionally body pigmentations. The resulting catalog was manually confirmed by an experienced researcher at CRC and any mark changes were confirmed by a second.

## *2.3 Constructing spatial capture-recapture dataset*

Spatial capture-recapture (SCR) builds on traditional capture-recapture methods by modeling the location of capture. An SCR approach (Royle & Young 2008) was employed to estimate the abundance of pilot whales near Kaua‘i based on photo-ID. SCR requires explicitly defining the study area, known as the state space (Sutherland, Royle, & Linden, 2019). The state space for each

study period was defined as any area within 14.7 km, which is referred to as the buffer, of survey effort during the study period. The buffer was chosen as 1.5 times the initial estimate of the spatial scale parameter,  $\sigma$ , which controls the rate at which detection probability declines with distance from an individual’s activity center (see below for a detailed description of the model and its parameters). This initial estimate of  $\sigma$  was decided with the RPSV function in the SECR package (Efford, 2023; R Core Team, 2024). The study area was divided into a regular grid with each cell acting as a potential “trap” in the SCR framework (Thompson, Royle & Garner, 2012). As a robustness check, multiple grid cell sizes were tested to ensure that different spatial resolutions did not meaningfully affect estimates of the spatial scale parameter or density. (Figure S1). The final cell size was selected to balance spatial resolution with computational efficiency while accommodating the spatial scale of pilot whale movements (Figure S1). Spatial encounter histories were constructed based on whether individuals were observed within each grid cell during each survey day. The data was organized into sessions (years or groups of years) (Figure 2) and occasions (individual survey days within sessions). Although the broader SCR community typically uses the term session for these year or multi-year groupings, they will be referred to here as study periods. Spatial encounter histories were constructed where  $y_{ijkl}$  indicates whether individual  $i$  was sighted in cell  $j$  during occasion  $l$  of study period  $k$ . The data  $y_{ijk}$  was treated as a Bernoulli random variable,  $y \sim \text{Bernoulli}(p_{ijk} * x_{jk})$ , where  $p_{ijk}$  represents the probability of encountering individual  $i$  in cell  $j$  during study period  $k$  at least once, and  $x_{jk}$  is an indicator variable where  $x_{jkl} = 1$  if cell  $j$  was visited during occasion  $l$  of study period  $k$ .



**Fig 2.** Sightings from 2011 to 2023 grouped into two-year study periods depicting sightings color-coded by population (island-associated as purple, pelagic as green, and unknown as orange) and the PMRF (red). There were no field efforts in 2019.

#### 2.4 Model framework and detection functions

SCR assumes that the encounter probability decreases with increasing distance of trap  $j$  from each individual's activity center, which represents the central point around which that individual's movements are distributed during the sampling period. This relationship is described by a detection function, which models the decline in encounter probability with increasing distance from the activity center. In the half-normal detection function,  $\lambda_0$ , represented the basal encounter rate or the expected detection probability when the activity center was directly at the trap location. The scale parameter,  $\sigma$ , determined how quickly detection probability decreased as distance,  $d_{i,j}$ , between the activity center of individual  $i$  and trap  $j$  increased.

The starting model began with constant values for density, detection probability, and spatial scale parameter ( $\sigma$ ), with each study period representing a single year. From this baseline, temporal grouping, population filtering, and covariate effects were systematically evaluated.

### *2.5 Temporally grouping data across years to improve precision*

To evaluate abundance trends while addressing sparse data in individual years, encounter histories were aggregated into two-year study periods. Pooling across two years increased the number of detections and spatial recaptures within each study period, reducing uncertainty in parameter estimates and improving model convergence. This approach assumed demographic closure within each two-year period, which is reasonable for a long-lived, resident species such as the short-finned pilot whale, where demographic turnover is expected to be minimal over short time spans (Kasuya et al., 1993). Importantly, the SCR framework also accommodated temporary emigration by allowing movement in and out of the study area (Royle & Young, 2008; Whittome et al., 2025).

### *2.6 Evaluating environmental and population covariates effects*

Analysis focused on how temporal variation, habitat covariates, and population structure might influence pilot whale density and detection near Kaua‘i and Ni‘ihau. Density was modeled as either constant across time or varying by study period to capture potential temporal fluctuations. Detection was always modeled as varying by sampling study period to account for differences in survey effort, environmental conditions, or observer effects among years. Given that the dataset spanned multiple years and was highly seasonal, an initial model allowed density to vary by study period, treating the system as “open” with respect to density. In the context of spatial capture-recapture, an “open” model allows individuals to enter or leave the population between study

periods, while still assuming demographic closure within each time period (Royle et al., 2013). This approach accounted for potential fluctuations in abundance across time periods without explicitly modeling survival or recruitment. Comparing this open model to one with constant density (i.e., a closed model with no temporal variation) allowed evaluation of whether density varied meaningfully over time and improved the ability to capture potential changes in pilot whale distribution across study periods. All continuous covariates were standardized (mean-centered and scaled by one standard deviation) prior to modeling to improve parameter convergence and interpretability of coefficients.

Environmental variables (depth and distance to shore) were incorporated into the model to account for habitat preferences known to influence pilot whale distribution and detectability. Depth was evaluated as a covariate on detection probability to represent third-order selection, which describes how individuals use habitat within their home ranges (Johnson 1980). Previous studies have shown that pilot whales in Hawaiian waters frequently associate with the 1000-2,500 m depth contour (Baird et al., 2013; Kratofil et al. 2023). While an individual’s home range may span a range of depths, whales may preferentially use specific ecologically relevant depth zones, increasing the probability of detection in those areas. Linear relationships were considered, but given this non-linear relationship with depth, detection probability was modeled as a quadratic function of standardized depth. Bathymetry data were obtained from the School of Ocean and Earth Science and Technology at a 50-meter resolution (Hawai‘i Mapping Research Group, 2012). The resulting detection model was:

$$\begin{aligned} \text{logit}(p_{i,j,k}) = & \log(p_0) - \left(\frac{1}{\sigma^2}\right) \times d_{ij}^2 + \beta_{\text{depth}} \times \text{depth}_j + \beta_{\text{depth}^2} \times \text{depth}_j^2 \\ & + \beta_{\text{study period}}_{[\text{study period}_k]} \end{aligned}$$

where  $p_0$  was the baseline encounter rate,  $d_{i,j}$ ,  $depth_j$  was the bathymetric depth at trap  $j$  and  $study\ period_k$  was an indicator for study period  $k$ .

Exploration of distance to shore allowed a covariate on density to capture second-order selection, reflecting how populations of pilot whales position their home ranges across the landscape relative to the coastline (Johnson 1980). Distance to shore was modeled as a linear standardized covariate to evaluate whether whale density increased or decreased with distance from the coastline. Island-associated pilot whales were expected to concentrate their activity offshore, but not so distant as to be separated from their preferred depth zones, particularly around the 1000-meter contour. Including distance to shore as a density covariate allowed broader spatial preferences to be modeled, capturing factors that influenced the distribution of home range centers across the study area.

The corresponding density model was:

$$\log(D_{jk}) = \beta_0 + \beta_{study\ period} [study\ period_k] + \beta_{dist\ to\ shore} \times dist_{to\ shore\ j},$$

where  $D_{jk}$  represented the expected density of activity centers in trap  $j$ ,  $\beta_0$  was the intercept,  $study\ period_k$  was the study period, and  $dist_{to\ shore\ j}$  was the distance from trap  $j$  to the nearest shoreline. Through incorporating these covariates, spatial and temporal variation in animal density were accounted for, and habitat-related influences on detection and activity center distribution were evaluated.

Differences in movement behavior and home range size between island-associated and pelagic pilot whales were considered. Because these groups were known to differ behaviorally when considering home range size, a population covariate was tested on the spatial scale parameter to

allow for population-level variation in home range size (Baird et al., 2017). Population assignments were defined previously by Cascadia Research Collective based on social network structure, association patterns, sighting history, and, when available, genetic or telemetry data (Mahaffy et al., 2015; Kratofil et al. 2023; Van Cise et al., 2017).

The corresponding spatial scale parameter model was:

$$\log(\sigma_{iz}) = \beta_{0,\sigma} + \beta_{population}[population_i]$$

Where  $\sigma_{iz}$  was the spatial scale parameter for individual  $i$  in population  $z$ ,  $\beta_{0,\sigma}$  was the intercept and  $\beta_{population}$  represented the population effect (ie. Island-associated, pelagic, or unknown). The oSCR package (Royle et al., 2016) inherently estimated separate parameter values for each population when included as a covariate. Individuals with uncertain population identity were included in the analysis, with their group assignment treated as a latent variable in the model likelihood, following the implementation described by Sutherland et al. (2019). Additionally, models were run excluding pelagic individuals entirely to generate abundance estimates specific to the island-associated community around Kaua‘i and Ni‘ihau.

**Table 1.** Parameter definitions following the notation of the oSCR package (Royle et al., 2016).

<i>Parameter</i>	<i>Symbol</i>	<i>Definition</i>	<i>Units</i>
<i>Baseline detection probability</i>	$p_0$	Probability of detecting an individual at its activity center when at its activity center (distance = 0)	Non-dimensional
<i>Scale of movement</i>	$\sigma$	Spatial scale parameter describing the rate at which detection decreases with distance from an activity center	Kilometers
<i>Density</i>	$D$	Number of individuals per unit area	individuals/km <sup>2</sup>
<i>Probability of inclusion</i>	$\psi$	Proportion of potential activity centers that belong to the actual population (superpopulation fraction)	Non-dimensional

## 2.7 Scaling density estimates to abundance estimates

SCR modeling provided a density estimate that was assumed constant throughout the defined state space. Total abundance was calculated by multiplying the estimated density by the area of the state space. A 14,000 km<sup>2</sup> state space was selected after comparing the state spaces for all study periods because it physically encompassed Kaua‘i and Ni‘ihau best while fully containing the spatial extent of all survey effort and sightings.

SCR abundance estimates represent only the portion of the population that is photographically distinctive through photo-identification protocols. The proportion of the distinctive population, also known as the mark rate, is essential for scaling estimates from identifiable individuals to the total population. The mark rate was calculated by determining, for each sighting, the proportion of high-quality photographs (Q3-Q4) of individuals classified as distinctive (D3-D4). Sightings with fewer than four individuals were excluded following Bradford et al. (2018). The mean mark rate was 59.69% (SD  $\pm$  17.06%) across all sightings and 58.55% (SD  $\pm$  17.54%) for the island-associated. Following Urian et al. (2015), the abundance estimate divided by the mark rate provided an estimate of the total population size. In this approach,  $\hat{N}$  represents the estimated abundance of marked individuals obtained from the SCR model, and  $\hat{P}$  is the mark rate provided by Cascadia Research Collective. This approach explicitly incorporates variance from both the SCR estimate and the mark rate into the final population variance. The total population size and its variance were calculated as:

$$\tilde{N} = \frac{\hat{N}}{\hat{P}} \text{ and } \text{var}(\tilde{N}) = \hat{N}^2 \left( \frac{\text{var}(\hat{N})}{\hat{N}^2} + \frac{\text{var}(\hat{P})}{\hat{P}^2} \right)$$

## 2.8 Model fitting and selection

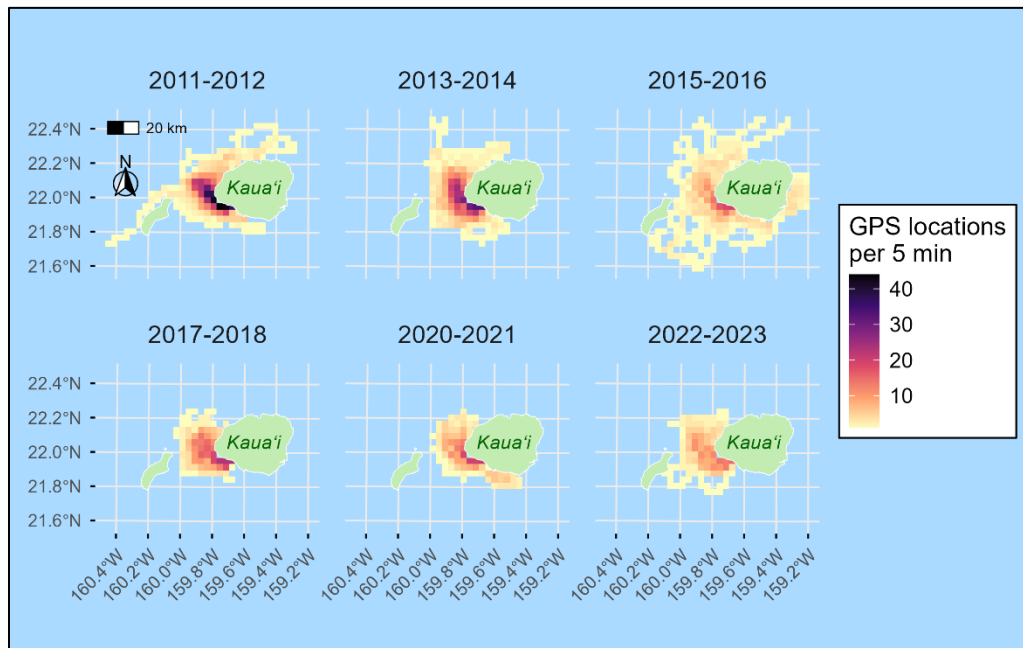
Eight candidate models were evaluated for the island-associated group and eight for all pilot whales utilizing Kaua‘i, incorporating different combinations of study period effects, habitat covariates (depth and distance to shore), and population effects on detection and density parameters. Models were fit using maximum likelihood estimation in the oSCR package (Royle et al., 2016) in R (R Core Team, 2024). Model selection followed an information-theoretic approach, using Akaike’s Information Criterion (AIC) to compare relative model support. For each candidate set, the model with the lowest AIC was considered the best-supported, with  $\Delta$ AIC values used to assess the degree of support for alternative models.

## 3. Results

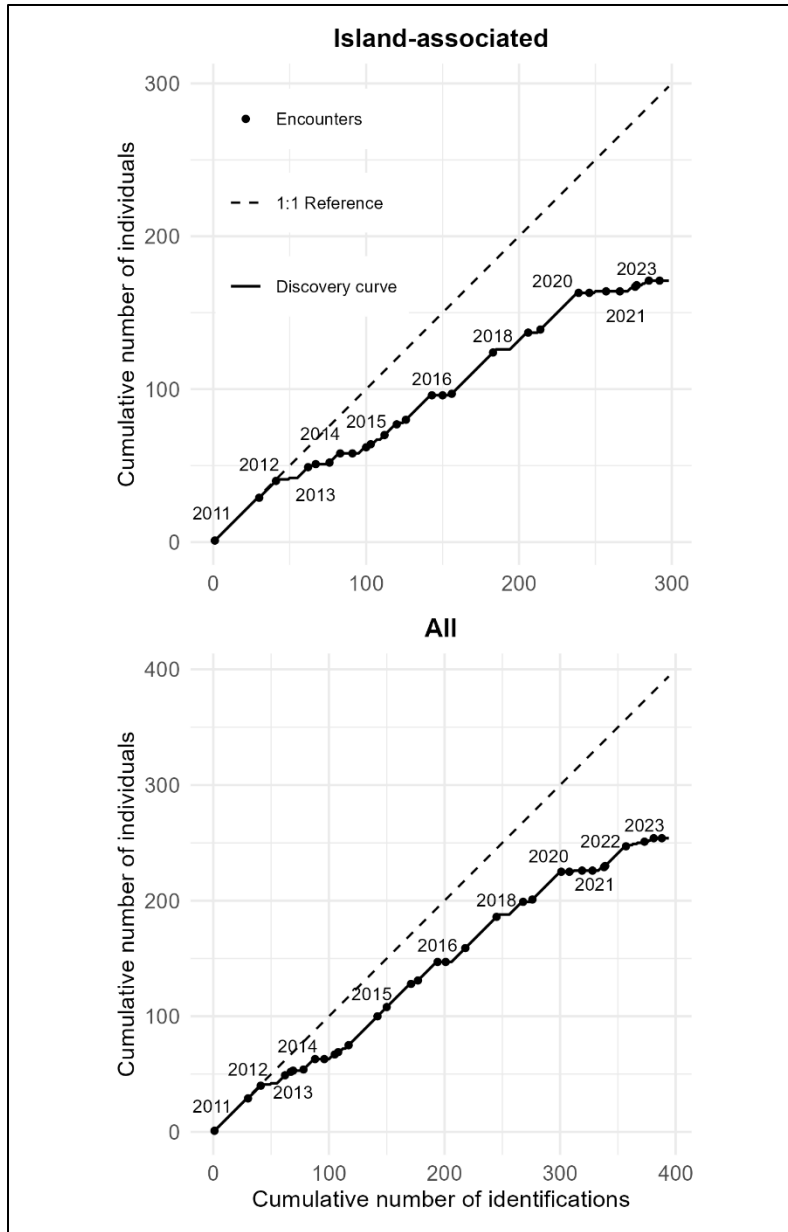
Between 2011 and 2023, CRC conducted 1,512 hours of surveys on-effort over 178 days across 20 field seasons, covering 23,416 km near Kaua‘i and Ni‘ihau (Figure 3). Survey effort was recorded in all grid cells, with 3.3% of grid cells experiencing both survey effort and pilot whale encounters. Surveys produced 45 pilot whale group encounters, with mean group size of  $23 \pm 14.8$  individuals. Encounters were distributed across the study area with 49% occurring between the 1000-m and 2500-m depth contour. From the encounters there were sighting histories of 237 distinctive or very distinctive individuals (Table 2, Figure 4). Individual sighting frequencies ranged from one to seven encounters with a mean of two ( $SD=1$ ). While 161 individuals (68%) were encountered only once, ten individuals (4.2%) were encountered  $\geq 5$  times, with the most frequently sighted individual recorded across seven encounters spanning 10 years (Figure 5). Mean number of distinctive individuals with good or excellent quality photos per encounter was  $9 \pm 2$ .

**Table 2.** Biennial summary of pilot whale sightings near Kaua‘i Island, including totals for island-associated, pelagic, and unknown individuals, unique distinctive individuals photographed, and within-period resightings. There was no effort in 2019.

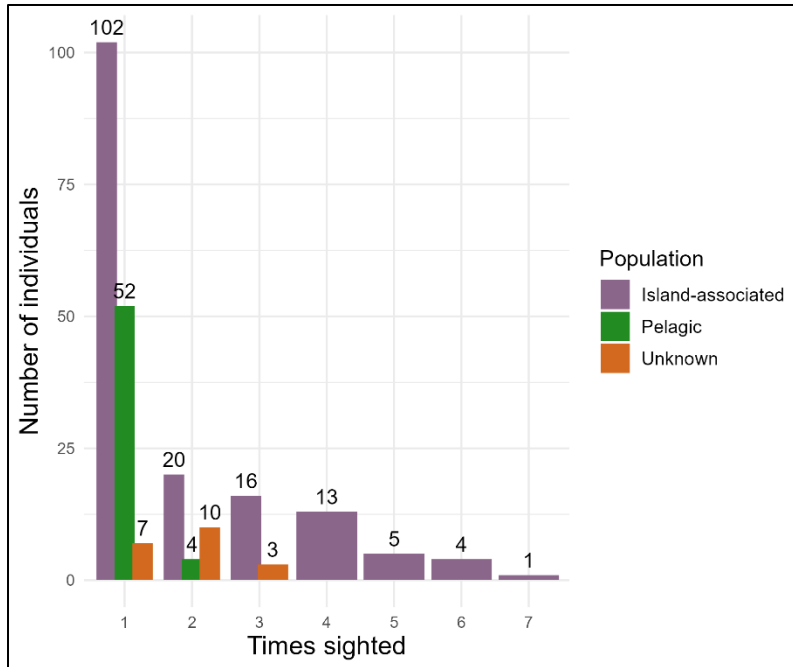
		2011-2012	2013-2014	2015-2016	2017-2018	2020-2021	2022-2023
<b>Number of Individuals</b>	<b>Island-associated</b>	66	45	71	56	38	22
	<b>Pelagic</b>	0	28	32	0	0	0
	<b>Unknown</b>	2	0	0	0	0	34
	<b>Total</b>	68	73	103	56	38	56
	<b>Unique</b>	65	60	98	41	30	35
	<b>Resightings</b>	3	13	5	15	8	21



**Fig. 3** Spatial distribution of trap effort near Kaua‘i and Ni‘ihau from 2011-2023. Effort is measured in GPS locations per 5 minutes, with darker colors (purple) indicating higher effort and lighter colors (yellow) indicating lower effort. Data are in two-year intervals representing study period grouping. There was no field effort in 2019.



**Fig. 4** Discovery curve for island associated (top) and all (bottom) pilot whales showing the cumulative number of identifications (x-axis) and the cumulative number of unique distinctive individuals identified (y-axis). Years indicate the start of each survey year, points are encounters, and the dashed line represents a 1:1 reference for comparison. Deviation below the 1:1 line indicates new identifications are accumulating more slowly suggesting repeated sightings of previously identified individuals.



**Fig. 5** Number of times each individual pilot whale was sighted near Kaua'i and Ni'ihau from 2011 to 2023, separated by population (island-associated as purple, pelagic as green, and unknown as orange).

### 3.1 Evaluating sensitivity of grid cell size and temporal groupings

Models were relatively insensitive to grid cell size (Table S1), showing minimal variation across cell sizes ranging from 1 km to 11 km. Given these minimal differences and following Royle & Turner (2022), who noted that grid cell size is not critical but should be chosen to reflect search effort across the survey region, a 4 km grid cell size was selected. This resolution balances computational efficiency with spatial precision while avoiding the grouping of spatially distinct sightings within single cells (Thompson et al., 2012). Annual study periods were too sparse to reliably fit models, leading to frequent convergence failures. Pooling data into two-year study periods improved convergence and reduced variance in abundance estimates by increasing detections and spatial recaptures. About half of the annual study period models failed to converge, while all two-year models converged successfully.

### 3.2 *Contrasting pelagic and island-associated individuals*

Pelagic individuals, identified through telemetry and photo-identification, ranged broadly across the Hawaiian archipelago and were therefore less likely to be detected during surveys conducted off Kaua‘i. Across all study periods, 56 pelagic individuals were identified, compared to 161 island-associated individuals, underscoring the contrast in spatial use and detectability between the two groups. Although the model incorporating pelagic and island-associated pilot whales was expected to reflect this spatial difference by estimating a larger spatial scale parameter ( $\sigma$ ) for pelagic individuals, indicating broader movement and larger home ranges, the results instead suggested the opposite, with pelagic whales exhibiting a smaller estimated  $\sigma$ . In contrast, density estimates for pelagic individuals were lower than those for island-associated whales, consistent with their wider-ranging movements and reduced availability within the survey grid. For example, in the model that combines pelagic and island-associated individuals, mean density across study periods decreased from 0.026 (SD  $\pm$  0.024) island-associated individuals/km<sup>2</sup> to 0.022 (SD  $\pm$  0.019) pelagic individuals/km<sup>2</sup>, equivalent to approximately 2.6 and 2.2 whales per 100 km<sup>2</sup>, respectively, while mean detection (0.006  $\pm$  0.003) remained constant.

### 3.3 *Assessing candidate models*

Models including a distance to shore effect predicted a negative linear relationship, which is inconsistent with literature of pilot whale distribution and movement (Mahaffy et al., 2015; Kratofil et al. 2023; Baird et al., 2017). These models were therefore omitted from further consideration. The remaining five candidate models for both groupings produced stable estimates.

For the island-associated group, the top-ranked model included study period effects on both detection and density, with depth included as a covariate on detection probability (AIC = 2427;

Table 3). The next best-supported model, which assumed constant density but retained study period effects and the depth covariate on detection, had an AIC of 2449 ( $\Delta AIC = 22$ ), indicating strong support for the top model. Models without depth covariates on detection had substantially higher AIC values ( $\Delta AIC > 300$ ), providing strong evidence for habitat effects on detection. Detection probability varied across study periods, while density estimates showed substantial temporal fluctuations over the study period.

When considering the model that included all pilot whales utilizing Kaua‘i, the pattern of model support remained consistent. The top model also included study period effects on detection and density, with depth as a covariate on detection probability (AIC = 3374; Table 4), and the next best model, which assumed constant density but retained study period effects and the depth covariate on detection, had a  $\Delta AIC$  of 29. The remaining models had  $\Delta AIC$  values exceeding 280, further supporting the inclusion of habitat effects on detection probability

**Table 3.** AIC values for the island-associated pilot whales near Kaua‘i.

<i>Model</i>	<i>Density (D)</i>	<i>Detection (p0)</i>	<i>Sigma (σ)</i>	<i>k</i>	<i>AIC</i>	<i>ΔAIC</i>	<i>weight</i>
1	D (~study period)	p0 (~study period + depth + depth <sup>2</sup> )	σ (~1)	15	<b>2427</b>	<b>0</b>	<b>1</b>
2	D (~1)	p0 (~study period + depth + depth <sup>2</sup> )	σ (~1)	10	2449	22	0
3	D (~study period)	p0 (~study period)	σ (~1)	13	2759	332	0
4	D (~1)	p0 (~study period)	σ (~1)	8	2787	360	0
5	D (~1)	p0 (~1)	σ (~1)	3	2800	373	0

**Table 4.** AIC values for island-associated and pelagic pilot whales near Kaua‘i.

<i>Model</i>	<i>Density (D)</i>	<i>Detection (p0)</i>	<i>Sigma (σ)</i>	<i>k</i>	<i>AIC</i>	<i>ΔAIC</i>	<i>weight</i>
1	D (~study period)	p0 (~study period + depth + depth <sup>2</sup> )	σ (~pop.)	17	<b>3374</b>	<b>0</b>	<b>1</b>
2	D (~1)	p0 (~study period + depth + depth <sup>2</sup> )	σ (~pop.)	12	3403	29	0
3	D (~study period)	p0 (~study period)	σ (~pop.)	15	3662	288	0
4	D (~1)	p0 (~1)	σ (~pop.)	5	3718	343	0
5	D (~1)	p0 (~study period)	σ (~pop.)	10	3721	347	0

### 3.4 *Best-supported model parameter estimates*

The top-ranked model for the island-associated group included study period effects on both detection and density, and depth on detection. Estimated density, abundance and detection varied across study periods (Table 5 and 6). Estimated baseline detection probability ranged from 0.0005 (95% CI: 0.00019-0.00135) to 0.0036 (95% CI: 0.00175-0.00727) over the study period, with a mean detection probability of 0.0023 (SD  $\pm$  0.0010) and peaking around the 2,000-meter zone (Figure 6 and 7). Estimated densities ranged from 0.0079 (95% CI: 0.0049 to 0.0128) to 0.0643 (95% CI: 0.0274 to 0.1508) whales/km<sup>2</sup>, which corresponds to approximately 0.8 to 6.4 whales per 100 km<sup>2</sup>, with a mean density of 0.025 (SD  $\pm$  0.019) whales/km<sup>2</sup> (about 2.5 whales per 100 km<sup>2</sup>). Corresponding abundance estimates ranged from 111 (95% CI: 68-180) to 901 (95% CI: 384-2112) marked individuals, with an overall mean abundance of 343 (SD  $\pm$  270) marked individuals (Figure 8). Applying the mark rate of 58.55% (SD  $\pm$  17.54%) to account for unmarked individuals resulted in a mean total abundance estimate of 587 (SD  $\pm$  494, Table 7). The spatial scale parameter was estimated at approximately 20.29 km (95% CI: 15.89–25.92 km) and remained constant across study periods, suggesting that pilot whales were detectable within a 20.29 km radius of their activity centers.

**Table 5.** Parameter estimates for the top-ranked model that included study period effects on both detection and density and depth as a covariate on detection for island-associated short-finned pilot whales near Kaua‘i.

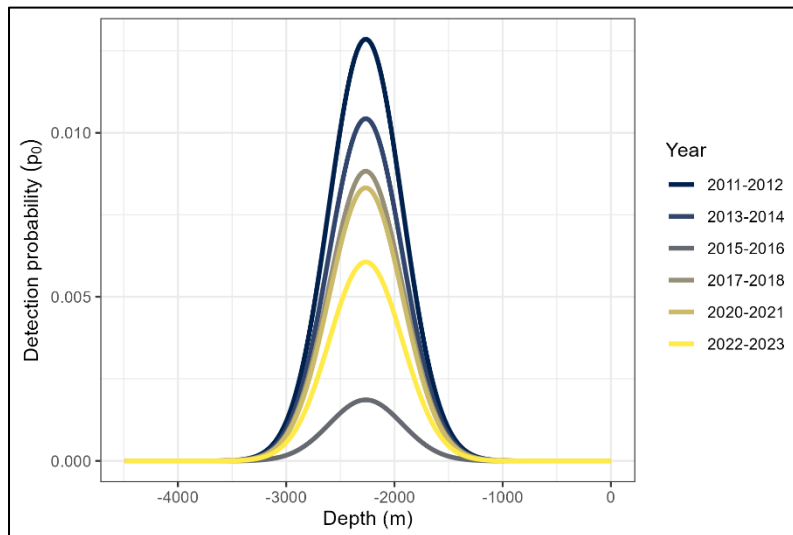
<i>Parameter</i>	<i>Maximum Likelihood Estimate</i>	<i>Standard Error</i>	<i>95% CI</i>
<i>p0 (Intercept)</i>	-5.6328	0.3655	(-6.349, -4.917)
<i>p0 2013-2014</i>	-0.2112	0.4067	(-1.008, 0.586)
<i>p0 2015-2016</i>	-1.9433	0.5245	(-2.971, -0.915)
<i>p0 2017-2018</i>	-0.3795	0.3810	(-1.126, 0.367)
<i>p0 2020-2021</i>	-0.4391	0.4633	(-1.347, 0.469)
<i>p0 2022-2023</i>	-0.7580	0.5462	(-1.828, 0.313)
<i>sigma (Intercept)</i>	9.9180	0.1248	(9.673, 10.163)
<i>Depth (standardized)</i>	-5.3356	0.4330	(-6.184, -4.487)
<i>Depth<sup>2</sup> (standardized)</i>	-5.5096	0.5898	(-6.666, -4.354)
<i>Density (Intercept)</i>	-1.5074	0.2019	(-1.903, -1.112)
<i>Density 2013-2014</i>	-0.5603	0.3212	(-1.190, 0.069)
<i>Density 2015-2016</i>	1.5363	0.4808	(0.594, 2.479)
<i>Density 2017-2018</i>	0.5850	0.3073	(-0.017, 1.187)
<i>Density 2020-2021</i>	0.5633	0.3854	(-0.192, 1.319)
<i>Density 2022-2023</i>	-0.1483	0.4695	(-1.068, 0.772)

**Table 6.** Predictions using the mean depth of 1527 m for the top-ranked model that included study period effects on both detection and density and depth as a covariate on detection for island-associated short-finned pilot whales near Kaua‘i. Density (*D*) is expressed as whales km<sup>2</sup>, abundance (*N*) as the estimated number of marked individuals, and detection probability (*p0*) as the baseline probability of detection. Values in parentheses denote 95% confidence intervals.

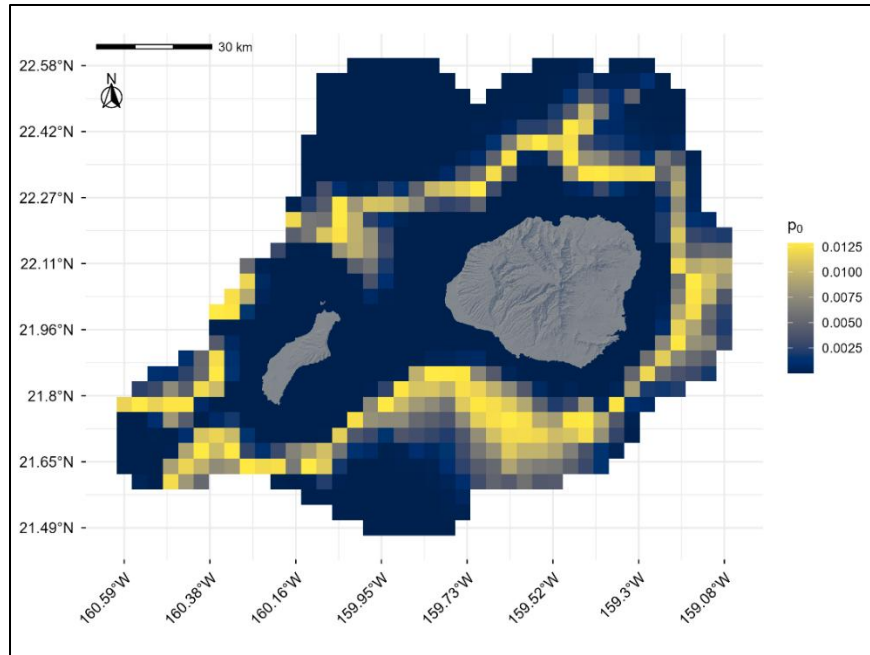
<i>Year</i>	<i>Density (km<sup>2</sup>)</i>	<i>CI 95% (km<sup>2</sup>)</i>	<i>Abundance</i>	<i>CI 95%</i>	<i>Detection</i>	<i>CI 95%</i>
2011-2012	0.0138	(0.0093-0.0206)	194	(130-288)	0.00357	(0.00175-0.00727)
2013-2014	0.0079	(0.0049-0.0128)	111	(68-180)	0.00289	(0.00149-0.00559)
2015-2016	0.0643	(0.0274-0.1508)	901	(384-2112)	0.00051	(0.00019-0.00135)
2017-2018	0.0248	(0.0157-0.0392)	348	(220-549)	0.00244	(0.00125-0.00476)
2020-2021	0.0243	(0.0128-0.0462)	340	(179-647)	0.00230	(0.00107-0.00493)
2022-2023	0.0119	(0.0052-0.0273)	167	(73-382)	0.00167	(0.00066-0.00424)

**Table 7.** Scaled abundance estimates based on a 58.55% mark rate and a mean depth of 1527 m for the top-ranked model of island-associated short-finned pilot whales near Kaua‘i. The model included study-period effects on both detection and density and depth as a covariate on detection. Abundance ( $N$ ) represents the estimated number of individuals by study period. Values in parentheses indicate 95% confidence intervals.

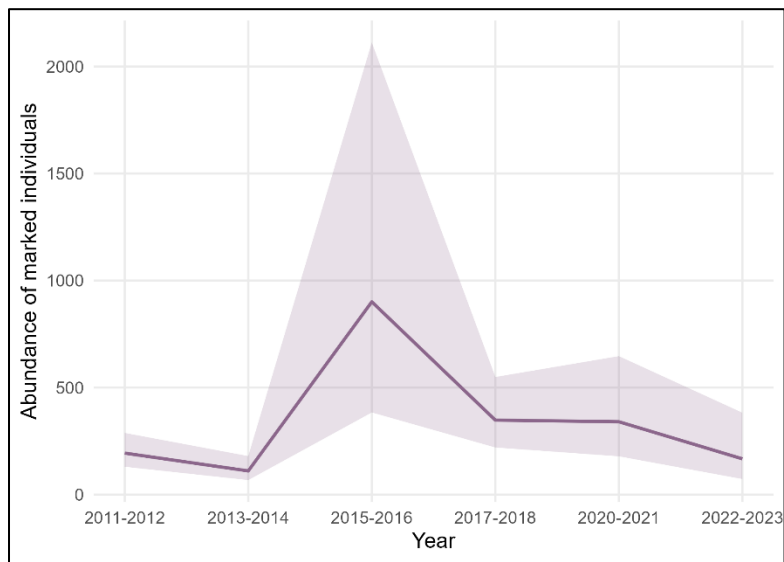
<i>Year</i>	<i>Population</i>	<i>Abundance</i>	<i>CI 95%</i>
2011-2012	Island-associated	331	(194-468)
2013-2014	Island-associated	189	(105-273)
2015-2016	Island-associated	1538	(606-2470)
2017-2018	Island-associated	594	(335-853)
2020-2021	Island-associated	581	(285-877)
2022-2023	Island-associated	285	(116-455)



**Fig. 6** Spatial capture-recapture model predictions for island-associated short-finned pilot whales near Kaua‘i. Predicted detection probability ( $p_0$ ) as a function of standardized depth, with each study period (i.e., pair of years) represented by a different color. Detection varies quadratically with depth.

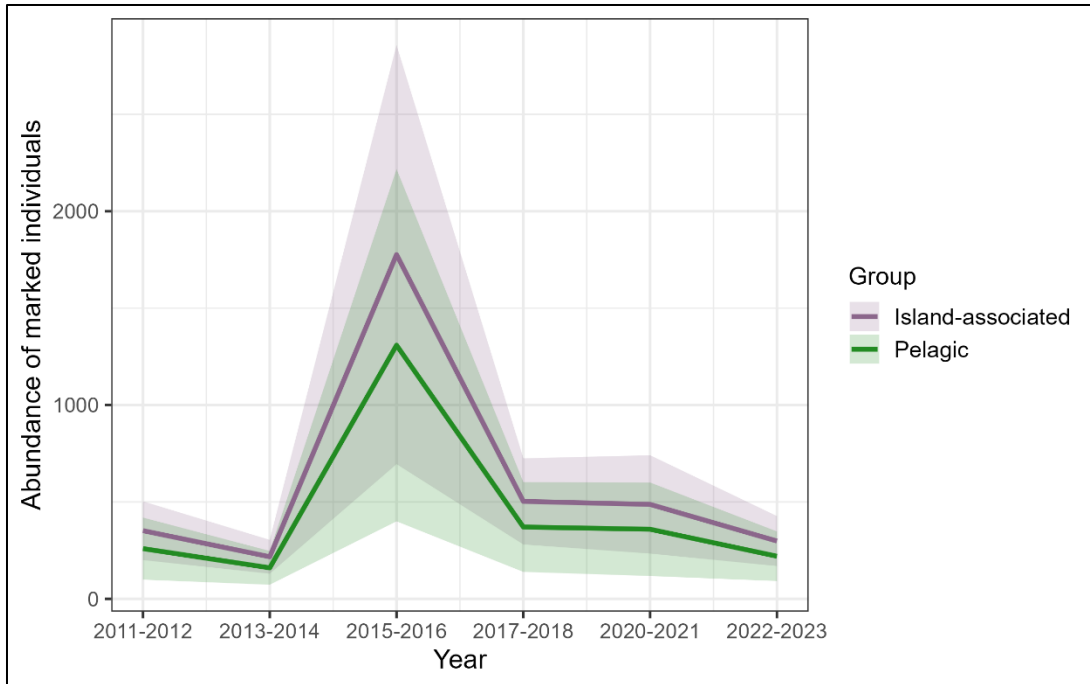


**Fig. 7** Map of predicted detection probability ( $p_0$ ) by depth for island-associated short-finned pilot whales near Kaua‘i and Ni‘ihau. Yellow areas indicate higher detection probability, while dark blue areas indicate low or no detection probability. Data from the first time period is shown but is representative of all study periods.



**Fig. 8** Spatial capture-recapture model predictions for island-associated short-finned pilot whales near Kaua‘i. Predicted abundance of marked individuals (in 14,000 km<sup>2</sup> state space) for each study period, with 95% confidence interval error bars indicating uncertainty around the estimates.

Based on the top-ranked model that included study period effects on both detection and density, depth on detection and population covariate on the spatial scale parameter, estimated density and abundance varied across years for both island-associated and pelagic (pelagic individuals utilizing Kaua‘i) pilot whales (Table 8, 9, and 10). Estimated baseline detection probability was the same for both pelagic and island-associated individuals ranging from 0.00091 (95% CI: 0.00035-0.00234) to 0.00989 (95% CI: 0.00562-0.01736) across study periods, with a mean value at 0.006 (SD  $\pm$  0.003) and peaking around the 2,000-meter zone. For the island-associated group, density ranged 0.009 (95% CI: 0.0064-0.0134) to 0.0757 whales/km<sup>2</sup> (95% CI: 0.032-0.178), equivalent to approximately 0.9 to 7.6 whales per 100 km<sup>2</sup>. Corresponding abundance estimates ranged from 130 (95% CI: 89-188) to 1,060 (95% CI: 452-2,485) marked individuals across study periods. For the pelagic group, density ranged from 0.007 (95% CI: 0.003-0.014) to 0.056 whales/km<sup>2</sup> (95% CI: 0.020-0.155), equivalent to approximately 0.7 to 5.6 whales per 100 km<sup>2</sup>. Corresponding abundance estimates ranged from 95 (95% CI: 47-196) to 781 (95% CI: 282-2,164) marked individuals in different pairs of years. Averaged across all years, mean density was 0.026 (SD  $\pm$  0.024) whales/km<sup>2</sup> for the island-associated group and 0.022 (SD  $\pm$  0.019) whales/km<sup>2</sup> for the pelagic group, equivalent to approximately 2.6 and 2.2 whales per 100 km<sup>2</sup>, respectively and corresponding to mean abundance estimates of 362 (SD  $\pm$  349) and 266 (SD  $\pm$  255) marked individuals (Figure 9). Accounting for the 59.69% (SD  $\pm$  17.06%) mark rate, the mean total abundance was 606 (SD  $\pm$  584) for the island-associated and 446 (SD  $\pm$  430) for the pelagic (Table 11). The spatial scale parameter indicated an average of 19.95 km (95% CI: 15.75-25.28) for island-associated and 8.85 km for pelagic (95% CI: 6.02-13.01).



**Fig. 9** Predicted abundance of marked individuals (in 14,000 km<sup>2</sup> state space) for each study period separated by population (island-associated as purple, pelagic as green), with 95% confidence interval error shading indicating uncertainty around the estimates.

**Table 8.** Parameter estimates for the top-ranked model that included study period effects on both detection and density, depth as a covariate on detection, and population as a covariate on sigma for island-associated and pelagic short-finned pilot whales near Kaua‘i.

<i>Parameter</i>	<i>Maximum Likelihood Estimate</i>	<i>Standard Error</i>	<i>95% Confidence Interval</i>
<i>p0 (Intercept)</i>	-5.255	0.337	(-5.916, -4.595)
<i>p0 2013-2014</i>	0.650	0.382	(-0.099, 1.398)
<i>p0 2015-2016</i>	-1.745	0.527	(-2.779, -0.712)
<i>p0 2017-2018</i>	0.032	0.375	(-0.702, 0.767)
<i>p0 2020-2021</i>	-0.008	0.451	(-0.893, 0.877)
<i>p0 2022-2023</i>	0.409	0.371	(-0.318, 1.135)
<i>Sigma (Intercept)</i>	9.901	0.121	(9.665, 10.138)
<i>Sigma (Pelagic)</i>	-0.813	0.224	(-1.253, -0.373)
<i>Depth (standardized)</i>	-2.425	0.199	(-2.815, -2.036)
<i>Depth<sup>2</sup> (standardized)</i>	-1.413	0.199	(-1.803, -1.024)
<i>Density 2013-2014</i>	-0.876	0.284	(-1.433, -0.319)
<i>Density 2015-2016</i>	-0.483	0.299	(-1.069, 0.104)
<i>Density 2017-2018</i>	1.620	0.496	(0.648, 2.591)
<i>Density 2020-2021</i>	0.358	0.335	(-0.299, 1.014)
<i>Density 2022-2023</i>	0.326	0.411	(-0.479, 1.131)
<i>Density 2013-2014</i>	-0.165	0.328	(-0.809, 0.479)
<i>Psi (Constant)</i>	-0.306	0.370	(-1.030, 0.419)

**Table 9.** Predictions using the mean depth of 1527 m for the top-ranked model that included study period effects on both detection and density, depth as a covariate on detection, and population as a covariate on sigma for the island-associated portion of the island-associated and pelagic short-finned pilot whale model. Density ( $D$ ) is expressed as whales  $\text{km}^2$ , abundance ( $N$ ) as the estimated number of marked individuals, and detection probability ( $p_0$ ) as the baseline probability of detection. Values in parentheses denote 95% confidence intervals.

<i>Year</i>	<i>Density (<math>\text{km}^2</math>)</i>	<i>CI 95% (<math>\text{km}^2</math>)</i>	<i>Abundance</i>	<i>CI 95%</i>	<i>Detection</i>	<i>CI 95%</i>
2011-2012	0.0150	(0.0095-0.0236)	210	(133-330)	0.00519	(0.00269-0.01000)
2013-2014	0.0093	(0.0064-0.0134)	130	(89-188)	0.00989	(0.00562-0.01736)
2015-2016	0.0757	(0.0323-0.1775)	1060	(452-2485)	0.00091	(0.00035-0.00234)
2017-2018	0.0214	(0.0132-0.0347)	300	(185-486)	0.00536	(0.00288-0.00996)
2020-2021	0.0208	(0.0107-0.0405)	291	(149-567)	0.00515	(0.00249-0.01062)
2022-2023	0.0127	(0.0081-0.0201)	178	(113-281)	0.00779	(0.00487-0.01246)

**Table 10.** Predictions, using the mean depth of 1527 m, for the top-ranked model that included study period effects on both detection and density, depth as a covariate on detection, and population as a covariate on sigma for the pelagic portion of the island-associated and pelagic short-finned pilot whales model. Density ( $D$ ) is expressed as whales  $\text{km}^2$ , abundance ( $N$ ) as the estimated number of marked individuals, and detection probability ( $p_0$ ) as the baseline probability of detection. Values in parentheses denote 95% confidence intervals.

<i>Year</i>	<i>Density (<math>\text{km}^2</math>)</i>	<i>CI 95% (<math>\text{km}^2</math>)</i>	<i>Abundance</i>	<i>CI 95%</i>	<i>Detection</i>	<i>CI 95%</i>
2011-2012	0.0110	(0.00463-0.02634)	155	(65-369)	0.00519	(0.00269-0.01000)
2013-2014	0.00682	(0.00333-0.01397)	95	(47-196)	0.00989	(0.00562-0.01736)
2015-2016	0.0558	(0.0201-0.1546)	781	(282-2164)	0.00091	(0.00035-0.00234)
2017-2018	0.0158	(0.00653-0.03821)	221	(91-535)	0.00536	(0.00288-0.00996)
2020-2021	0.0153	(0.00577-0.04058)	214	(81-568)	0.00515	(0.00249-0.01062)
2022-2023	0.00936	(0.00422-0.02078)	131	(59-291)	0.00779	(0.00487-0.01246)

**Table 11.** Scaled abundance estimates based on a 59.69% mark rate and a mean depth of 1527 m for the top-ranked model of short-finned pilot whales near Kaua‘i. The model included study-period effects on both detection and density, depth as a covariate on detection, and population as a covariate on sigma. Abundance ( $N$ ) represents the estimated number of individuals by study period and population assignment. Values in parentheses indicate 95% confidence intervals.

<i>Year</i>	<i>Population</i>	<i>Abundance</i>	<i>CI 95%</i>
2011-2012	Island-associated	352	(200-503)
2013-2014	Island-associated	217	(130-304)
2015-2016	Island-associated	1776	(695-2857)
2017-2018	Island-associated	503	(281-725)
2020-2021	Island-associated	487	(234-741)
2022-2023	Island-associated	298	(170-427)
2011-2012	Pelagic	259	(99-419)
2013-2014	Pelagic	160	(73-247)
2015-2016	Pelagic	1309	(400-2217)
2017-2018	Pelagic	370	(139-602)
2020-2021	Pelagic	359	(118-600)
2022-2023	Pelagic	220	(92-347)

#### 4. Discussion

This study provides the first spatially explicit abundance estimates for short-finned pilot whales near Kaua‘i and Ni‘ihau, with a focus on the island-associated subset of the western community. Using SCR methods on a long-term non-systematic photo-identification dataset, mean

abundance was estimated at 343 (SD  $\pm$  270) marked individuals for island-associated whales and 628 (SD  $\pm$  432) marked individuals when modeling pelagic and island-associated together. After adjusting for the 58.55% (SD  $\pm$  17.54%) and 59.69% (SD  $\pm$  17.06%) mark rates, the total abundance estimate corresponded to 587 (SD  $\pm$  494) and 1052 (SD  $\pm$  746) individuals, respectively. Abundance varied across years, fluctuating throughout the 13-year study period. These results demonstrate that SCR can effectively utilize non-systematic datasets to produce robust estimates for highly mobile marine mammals where systematic surveys are logistically challenging.

The top-supported model indicated that both density and detection probability varied over time, with detection strongly influenced by a quadratic relationship with depth from the 1,500 to 3,000 m zone, decreasing at greater depths. This is consistent with previous findings that short-finned pilot whales associate with slope waters between 1,000 and 2,500 m (Baird et al., 2013; Abecassis et al. 2015; Kratofil et al., 2023).

#### *4.1 Temporal variation and changes in abundance*

Abundance estimates fluctuated across study periods, with the largest fluctuation occurring in study period 2015-2016. The high estimate was likely driven by the addition of many new cataloged individuals during those two years (Figure 4), rather than a true population increase, as shown by the high number of unique individuals from both populations (98; 41% of total; Table 2) and the low number of resightings (5). Given their long lifespan and slow reproductive rate (females can live for more than 60 years (Kasuya & Marsh, 1984)), substantial demographic changes within a few years are unlikely. Additionally, the use of a state space that included only the Kaua‘i portion of the western community’s range, which extends to O‘ahu (Baird et al., 2021),

may have contributed to the observed fluctuations. Therefore, short-term variation in abundance estimates should be interpreted cautiously.

#### *4.2 Differences between island-associated and pelagic whales*

Differences between island-associated and pelagic whales align with previous studies showing distinct movement and residency patterns (Mahaffy et al., 2015; Baird, 2016; Van Cise et al., 2017). Island-associated whales had higher densities within the survey area, while pelagic whales were sighted less frequently, reflecting their broader ranges and lower probability of being encountered off Kaua‘i. Surprisingly, the spatial scale parameter ( $\sigma$ ) for pelagic whales was smaller than expected, likely due to limited overlap between their home ranges and survey effort rather than true movement differences (Baird et al., 2017). Future analyses could integrate telemetry data to better distinguish detection processes from true space use. Although we attempted to incorporate telemetry data in this study, the models did not converge, likely because the sighting data were too sparse to support that level of complexity. Work by Badger et al. (2024) demonstrates an alternative Bayesian framework for combining telemetry and photo identification data, but a direct comparison with our SCR-based approach is beyond the scope of this study.

#### *4.3 Methodological considerations and limitations*

While SCR provides a robust approach for estimating abundance from non-systematic surveys, several limitations should be considered. First, detection probability was uniformly low ( $<0.01$ ), reflecting both the low encounter rates typical of a sparsely distributed, low density, wide-ranging species and the spatially limited survey coverage, contributing to wide confidence intervals. Second, although observer effort is assumed constant across field efforts, variation in personnel experience and weather may introduce bias. Third, while photo-ID matching is assumed to be

accurate, high rates of mark change in pilot whales (Mahaffy, 2012) may lead to misidentification and biased capture histories, although the use of association data helps mitigate these issues. Additionally, some encounters were directed by acoustic detections from the Navy or by reports from tour operators, introducing heterogeneity in the encounter probability. In this case, acoustically assisted detections likely increase the probability of encountering groups that may otherwise have remained undetected, which could lead to inflated detection probabilities and potential underestimation of true abundance if treated as equivalent to independent survey effort (Royle et al., 2013). Ideally, these detections would be incorporated directly into the SCR model, but the current framework does not accommodate encounter-level covariates. Given the limited dataset, all encounters were included in the analysis. Survey effort was spatially uneven due to sea conditions. Strong trade winds and swell limited access to the windward side of Kauaʻi, concentrating surveys along the leeward coast, and the distance to Niʻihau restricted coverage there as well. Although effort was variable across space, SCR explicitly models detection as a function of effort and estimates the spatial scale parameter, allowing individuals to move throughout the state space preventing bias from unsampled regions. While the western community ranges beyond the focal survey area toward Oʻahu, movement beyond the surveyed extent is likewise accommodated through the estimated spatial scale of detection.

SCR models assume spatial independence among individuals, an assumption that is violated in pilot whales because they occur in social units/clusters (Mahaffy et al., 2015). Empirical studies have shown that such grouping does not typically bias SCR estimates (McFarlane et al., 2020), except under extreme grouping scenarios (Bischof et al., 2020; Dupont et al., 2023).

Including distance to shore as a linear covariate produced biologically unrealistic predictions and was therefore excluded. The result is likely influenced by the state space, which focused on

Kaua‘i/Ni‘ihau. Extending to O‘ahu was not feasible due to sparse effort there, so the full island-associated range was not represented. A larger state space in future work could capture broader movements and reveal a more meaningful relationship with distance to shore.

#### *4.4 Conservation and management implications*

These results highlight the importance of treating the island-associated pilot whales near Kaua‘i as a DIP. With an estimated abundance of only 587 (SD  $\pm$  494) individuals, this community is relatively small and potentially vulnerable to localized threats. The overlap of their core habitat with the PMRF raises particular concern, as these whales spend nearly one-third of their time in areas where mid-frequency active sonar is regularly used (Baird et al., 2017). Although size fluctuates, chronic or repeated disturbance could lead to long-term behavioral or demographic effects that are not yet reflected in abundance trends. Continuous monitoring of this DIP is therefore important, particularly during years of increased naval activity such as the RIMPAC exercises.

#### *4.5 Future directions*

As data accumulate, future work should aim to refine movement and abundance estimates by integrating telemetry data within SCR frameworks, allowing for more accurate modeling of detection probability and home range size. Incorporating social network data may also help account for non-independence among detections. Modeling sea state as a covariate on the detection function could also reduce unexplained variability in encounter probability. Incorporating photo-ID data beyond Kaua‘i to include O‘ahu could clarify connectivity within the western community and potentially dampen some of the inter-annual variability in estimates caused by movements of individuals within the community. Finally, coupling SCR estimates with environmental covariates

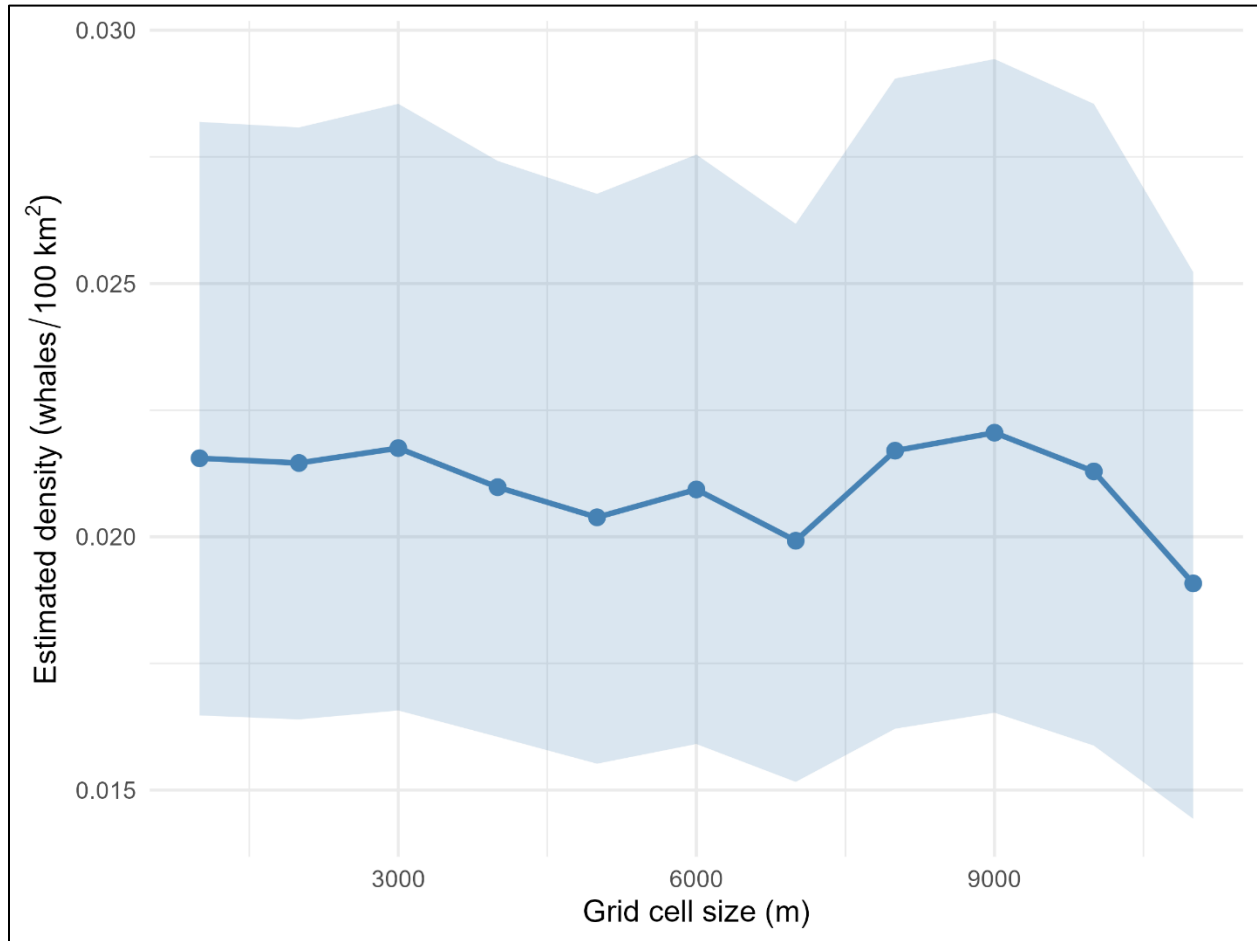
such as prey availability, oceanographic features (e.g., currents, seamounts), environmental cycles (e.g., lunar phase), and climate indices (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation) could help identify drivers of pilot whale distribution and abundance. Previous studies have shown that diving behavior and odontocete detections in Hawai‘i are influenced by lunar and oceanographic conditions (e.g., Owen et al. 2019; Ziegenhorn et al. 2023a, 2023b), highlighting the importance of incorporating these factors into future modeling efforts.

## APPENDIX A. SUPPLEMENTAL TABLES

**Table S1.** Annual summary of pilot whale sightings near Kaua‘i Island, including totals for island-associated, pelagic, and unknown individuals, unique distinctive individuals photographed, and within-year resightings. There were no sightings in 2017 and no effort in 2019.

		2011	2012	2013	2014	2015	2016	2018	2020	2021	2022	2023
<b>Number of Individuals</b>	<b>Island-associated</b>	40	26	9	36	31	40	56	7	31	0	22
	<b>Pelagic</b>	0	0	0	28	21	11	0	0	0	0	0
	<b>Unknown</b>	0	2	0	0	0	0	0	0	0	34	0
	<b>Total</b>	40	28	9	64	52	51	56	7	31	34	22
	<b>Unique</b>	39	26	9	51	52	46	41	7	23	18	17
	<b>Resightings</b>	1	2	0	13	0	5	15	0	8	16	5

## APPENDIX B. SUPPLEMENTAL FIGURES



**Fig S1.** Estimated density of island-associated marked individuals (whales/100 km<sup>2</sup>) as a function of grid cell size.

The solid line shows the mean estimated density across study periods, assuming constant parameter values. The shaded blue area represents the 95% confidence interval.

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