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Abstract

Twenty-four species of cetaceans (18 odontocetes, 6 mysticetes) regularly occur in the U.S. Exclusive Economic Zone of the Hawaiian Islands (Hawaiian EEZ). Abundance estimates are needed to evaluate the impacts of human activities in population assessments of these species. The Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) is a recurring ship-based, line-transect survey designed to estimate cetacean abundance in the entirety of the Hawaiian EEZ. Given the vast study area, two ships operating a total of approximately 180 days within the summer-fall period are required to complete each HICEAS. To date, HICEAS has been conducted in 2002, 2010, and 2017. Low encounter rates in the study area require that sightings of the same and similar species be pooled with sightings from previous line-transect surveys when estimating detection functions. Thus, estimating cetacean abundance during HICEAS 2017 offered an opportunity to update abundance estimates from HICEAS 2002 and 2010 using the most current detection functions and new estimates of trackline detection probabilities that consider the effect of survey sighting conditions. Group size and Beaufort sea state were the most important factors affecting the detectability of cetacean groups. Abundance was estimated for 21, 19, and 18 species in 2002, 2010, and 2017, respectively, with 16 species (14 odontocetes, 2 mysticetes) accounted for in all HICEAS years. Across all species and years, abundance point estimates range from 137 blue whales (*Balaenoptera musculus*) in 2010 to 76,375 rough-toothed dolphins (*Steno bredanensis*) in 2017. The low encounter rates led to high CVs (range, 0.27 to 1.71) for most estimates and low power to detect trends in abundance during the study period. Additionally, random variation in the sampling process and sighting attributes, along with interannual variation in oceanographic conditions within the Hawaiian EEZ, had pronounced effects on the abundance estimates, further complicating comparisons among years. Habitat-based modeling, satellite tagging, photo-identification, acoustic analyses, and simulation approaches can provide additional temporal and spatial inference that may be needed to assess and manage high priority species.

Introduction

Twenty-four species of cetaceans, including 18 odontocetes and 6 mysticetes, regularly occur in the U.S. Exclusive Economic Zone surrounding the Hawaiian Islands (hereafter referred to as the 'Hawaiian EEZ'). Within the Hawaiian EEZ, there are 39 populations from these species currently recognized in the Stock Assessment Reports (SARs) mandated by the U.S. Marine Mammal Protection Act for marine mammal populations in U.S. waters (Carretta et al. 2020). The structure and distribution of these Hawaiian-EEZ populations vary by species. Island-associated populations have been recognized for five of the odontocete species (Carretta et al. 2020), and putative island-associated populations have been suggested for at least six more (Albertson et al. 2017; Baird 2016; Oleson et al. 2013; Van Cise et al. 2017). For mysticete species, only one species uses the Hawaiian EEZ year-round, but of the remaining seasonal migrants, only one species demonstrates strong island-association. While island processes strongly influence the occurrence and distribution of cetacean populations in the Hawaiian EEZ (e.g., Abecassis et al. 2015; Woodworth et al. 2012), all species are represented by a population that spends some portion or most of its time in pelagic waters.

Abundance estimates are an important component of the SARs and are needed to evaluate the impacts of human activities on each population. While some island-associated populations can be routinely surveyed by small boats launched from shore (e.g., Baird et al. 2013; Pack et al. 2017), surveying for cetaceans within the entirety of the Hawaiian EEZ requires a larger-scale, ship-based effort. The Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) is a recurring ship-based, line-transect survey designed to estimate cetacean abundance in the Hawaiian EEZ. Given the large study area (about 2,500,000 km^2), two ships operating a total of approximately 180 days within the summer-fall period are needed to complete each HICEAS. To date, a HICEAS has been conducted in 2002, 2010, and 2017, with HICEAS 2002 carried out by the NOAA Fisheries Southwest Fisheries Science Center (SWFSC) and HICEAS 2010 and HICEAS 2017 accomplished as a collaborative effort between the SWFSC and the Pacific Islands Fisheries Science Center (PIFSC). HICEAS 2017 was conducted as part of the Pacific Marine Assessment Program for Protected Species (PacMAPPS), a collaborative effort between NOAA Fisheries, the U.S. Navy, and the Bureau of Ocean Energy Management (BOEM) to collect data necessary to produce updated abundance estimates of cetaceans in the Hawaiian EEZ.

The HICEAS in 2002 resulted in the first abundance estimates for most cetacean species in the Hawaiian EEZ (Barlow 2006). These estimates were obtained using design-based, line-transect analysis methods (Buckland et al. 2001), specifically a multiple-covariate estimation approach (Marques and Buckland 2004). Following HICEAS 2010, Bradford et al. (2017) adapted this estimation approach to produce design-based estimates of cetacean abundance in the Hawaiian EEZ during 2010. While design-based estimates of abundance should be unbiased (Thomas et al. 2007), they are derived from a single estimate of average density for the study area or survey strata. However, marine mammal management often requires spatially-explicit density estimates at finer spatial scales (e.g., Redfern et al. 2017). Model-based line-transect methods estimate density as a function of habitat or spatial covariates allowing abundance to be estimated at spatial scales of relevance to management (Hedley and Buckland 2004) and thus have become the preferred approach for analyzing cetacean line-transect data (Bouchet et al. 2019). A model-based approach was used to estimate the density and distribution of nine cetacean species in the central North Pacific, including the Hawaiian EEZ, following HICEAS 2002 (Becker et al. 2012) and HICEAS 2010 (Forney et al. 2015). Although sample sizes were low for some species and several sources of potential bias were identified, the resulting model-based abundance estimates were broadly similar to the corresponding design-based estimates.

With the completion of HICEAS 2017 (Yano et al. 2018), abundance estimation of cetaceans in the Hawaiian EEZ during 2017 can be pursued. Given recent advances in the estimation framework and the quality of available environmental data, model-based estimation is the method of choice and has been carried out for the pelagic populations of nine species (Becker et al. In Review). However, sample sizes are not sufficient to use a model-based approach for all sighted species, so design-based abundance estimation is needed for the remaining species. Further, design-based estimates are useful for comparing to model-based estimates (Thomas et al. 2007). Therefore, the overarching objective of this study is to estimate the abundance of cetacean populations sighted during HICEAS 2017 using design-based methods. With the broad spatial survey coverage and related lack of sightings from island-associated populations, the estimates are of the pelagic populations for species where both are recognized.

Low encounter rates in the study area necessitates pooling sightings of the same and similar species with sightings from previous SWFSC and PIFSC line-transect surveys when estimating the detection functions (Barlow 2006; Bradford et al. 2017). Thus, estimating cetacean abundance during HICEAS 2017 offered an opportunity to update abundance estimates from HICEAS 2002 (Barlow 2006) and HICEAS 2010 (Bradford et al. 2017) using the most current detection functions, as well as new estimates of trackline detection probabilities that consider the effect of survey sighting conditions (Barlow 2015). The specialized data collection protocols associated with sightings of false killer whales (*Pseudorca crassidens*) requires additional analytical considerations (Bradford et al. 2014). The design- and model-based abundance estimation of this species in 2002, 2010, and 2017 is detailed in a separate study (Bradford et al. 2020), although the resulting design-based estimates are included herein for completeness.

Methods

Data Collection

The design and implementation of the HICEAS in 2002, 2010, and 2017 have been described in detail (Barlow 2006; Bradford et al. 2014; Bradford et al. 2017; Yano et al. 2018). In short, each HICEAS was conducted aboard two NOAA ships within the Hawaiian EEZ during the summer and fall. For HICEAS 2002, the study area was surveyed from the 52-m *David Starr Jordan* from 6 August to 27 November 2002 and from the 53-m *McArthur* from 19 October to 25 November 2002. For HICEAS 2010, the study area was surveyed from the 68-m *McArthur II* from 13 August to 1 December 2010 and from the 68-m *Oscar Elton Sette* from 2 September to 29 October 2010. For HICEAS 2017, the study area was surveyed from the *Oscar Elton Sette* from 6 July to 10 October 2017 and from the 64-m *Reuben Lasker* from 26 August to 1 December 2017. The survey speed of each ship was 18.5 km/h (10 kt).

The systematic survey design for each HICEAS consisted of parallel transect lines spaced approximately 85 km apart and oriented WNW to ESE, providing comprehensive coverage of the study area (Barlow 2006; Bradford et al. 2014; Bradford et al. 2017; Yano et al. 2018). The same transect lines were used for HICEAS 2002 and HICEAS 2017, while the transect lines for HICEAS 2010 were placed midway between each of the lines used in 2002 and 2017. Additional parallel transect lines were established halfway between the main lines within 140 km of the main Hawaiian Islands (MHI) during HICEAS 2002 (Barlow 2006), resulting in a higher density of systematic survey effort within this MHI stratum compared to the outer-EEZ stratum (Figure 1A). Systematic survey effort was unstratified during HICEAS 2010 (Bradford et al. 2014; Bradford et al. 2017) and thus was uniform throughout the Hawaiian EEZ (Figure 1B). Survey effort was again stratified between the MHI and the outer-EEZ during HICEAS 2017, with the higher density of survey effort within the MHI stratum accomplished by surveying along routes used to deploy or recover drifting acoustic spar buoy recorders (Yano et al. 2018). While these routes were originally assumed to represent randomized transects, they were found to have oversampled shallow areas close to land within the MHI stratum and were therefore not counted as systematic transects (Bradford et al. 2020). Thus, systematic survey effort during HICEAS 2017 was uniform throughout the Hawaiian EEZ (Figure 1C).

In addition to the systematic survey effort on established design-based transect lines, the visual observation team typically remained on-effort following standard observation protocols while transiting to and from ports, between transect lines, and during other survey-specific deviations from the transect lines (e.g., the aforementioned drifting acoustic recorder routes). This nonsystematic effort differed from off-effort periods when the observers were not following standard observation protocols (e.g., during inclement weather or after sighting a cetacean). Cetacean sightings made during nonsystematic effort and while off-effort were not suitable for estimating cetacean abundance because those sightings were not detected on the systematic transect lines. However, nonsystematic-effort sightings were used to estimate detection functions because the observation protocols were the same during all on-effort periods.

The SWFSC and PIFSC have been collecting cetacean line-transect data throughout the Pacific Ocean using consistent observation protocols (Kinzey et al. 2000) since 1986 and 2009, respectively. Visual observation teams were made up of six observers who rotated through three positions on the flying bridge of the ship and searched for cetaceans from 90° left to 90° right forward of the vessel. A port and starboard observer each searched with 25× binoculars, and a center data recorder used unaided eyes. When a cetacean group was sighted, the initial bearing and radial distance to the sighting were recorded and used to calculate the perpendicular distance from the group to the ship's trackline. When the sighting was within a strip width of 5.6 km (3 nmi) from the trackline, the ship diverted from the trackline to the group so that species, species composition (for mixed-species groups), and group size (recorded as an independent "best," high, and low estimate for each observer) could be determined (Kinzey et al. 2000). Environmental data, including Beaufort sea state, were also collected for each sighting. For some sightings, once group size estimates were obtained and if weather conditions and animal behavior allowed, a small boat was launched from the ship to collect photo-identification images and biopsy samples of individuals in the group.

If the species of a sighting could not be identified, the lowest possible taxonomic category was applied (Table 1). During each HICEAS, an acoustics team worked simultaneously to but independently of the visual observation team, using a hydrophone array towed behind each ship (with the exception of the *McArthur* in 2002) to detect cetacean vocalizations during daylight hours. The observers were not informed of acoustic detections, and the acoustic detections were not included in the abundance estimation. However, systematic-effort sightings not identified to species from HICEAS 2010 and HICEAS 2017 (when more acoustic data were collected and analyzed) were compared to the species classification results from simultaneous acoustic detections (if available) for possible insights into species identification.

Abundance Estimation

The multiple-covariate line-transect methods (Buckland et al. 2001; Marques and Buckland 2004) used herein to estimate the abundance of cetaceans in the Hawaiian EEZ in 2002, 2010, and 2017 are largely the same methods used by Bradford et al. (2017) following HICEAS 2010, which were adapted from Barlow (2006) following HICEAS 2002. In brief, given the low cetacean encounter rates in the Hawaiian EEZ (Barlow 2006; Bradford et al. 2017), sample sizes for each species sighted during each HICEAS were insufficient for modeling the detection functions. Thus, all HICEAS sightings were pooled with sightings made during other SWFSC and PIFSC line-transect surveys from 1986 to 2016. The pooled sightings included both systematic- and nonsystematic-effort sightings and were limited to the central Pacific (defined as the area from 5° S to 40° N, and from 175° E to 120° W) to minimize heterogeneity resulting from geographical differences in species associations and behavior.

Even after pooling sightings across surveys, sample sizes for many species remained inadequate for estimating a detection function. Therefore, sightings of species with similar detection characteristics were also combined. The same species pools used by Bradford et al. (2017), which included 6 multi-species pools and a pool for pantropical spotted dolphins (*Stenella attenuata*), were formed in the present analysis. However, to account for species not sighted on systematic effort during HICEAS 2010, an additional pool was formed for spinner dolphins (*S.* spp.), and minke whales (*Balaenoptera acutorostrata*) and *Kogia* spp. were added to the multi-species pool of cryptic whales with small group sizes (see Table 2 for the composition of each pool).

A half-normal model (with no adjustments) was used to estimate the detection probabilities for the sightings in each species pool as a function of perpendicular distance from the trackline and of relevant covariates. Only half-normal models were used because they exhibit greater stability when fitting cetacean sighting data (Gerrodette and Forcada 2005). The 5–10% most distant sightings in each species pool were truncated to improve model fit (Buckland et al. 2001), although no truncation distance exceeded the 5.6-km survey strip width. The evaluated covariates consisted of the following:

- *Beaufort* (Beaufort sea state),
- *group size* (the natural logarithm of the sighting group size, which includes the total number of individuals in mixed-species groups),
- *cruise number* (the number assigned to each survey on a given ship in a given year),
- *ship* (the survey ship),
- *year* (the survey year), and
- *species* (the most abundant species within a group).

*Beaufor*t and *group size* were treated as continuous variables and the other covariates were treated as categorical variables, which were tested only if there were at least 10 observations for each factor level. Covariate models were built using a forward stepwise procedure and were selected using Akaike's information criterion corrected for small sample size (AICc; Hurvich and Tsai 1989).

Given individual observers tend to underestimate cetacean group sizes (e.g., Gerrodette et al. 2019), correction factors were applied to the "best" estimates of sighting group size made by observers who were calibrated during previous SWFSC surveys (Gerrodette and Forcada 2005). An indirect regression-based calibration method was then used to calibrate noncalibrated observers relative to the calibrated observers (Barlow 1995; Barlow and Forney 2007). The weighted geometric mean of the calibrated estimates of group size made by each observer (weighted by the inverse of the mean squared estimation error) was the sighting group size used to model the detection function. To derive the number of individuals by species in mixed-species sightings as needed to estimate density, the sighting group size was multiplied by the proportion of each species present (averaged over all observers). When the most abundant species within a mixed-species sighting was not one of the pooled species, the factor label for the *species* covariate was labeled as "other" to account for the collective influence of nonpooled species on the detection function (Table 2). For multi-species pools with too few "other" sightings to test the *species* covariate, the set of "other" sightings was examined in closer detail. If the set of sightings was considered unnecessary for estimating the detection function (e.g., sightings were outside the Hawaiian EEZ or made while on nonsystematic effort), the set was removed from the pool so that a species effect could be evaluated (Table 2).

Given the estimated covariate detection function and the systematic-effort sightings within the established truncation distance, a Horvitz-Thompson-like estimator (Marques and Buckland 2004) was used to estimate the density (D) of each species in each survey stratum in each HICEAS year:

$$D = \frac{1}{2 \cdot L \cdot g(0)} \sum_{j=1}^{N} f(0, \boldsymbol{c}_j) \cdot s_j \qquad (1)$$

Where:

L = the length of the systematic transect effort completed in the stratum,

$g(0)$ = the trackline detection probability (i.e., perpendicular distance = 0),

$f(0,\boldsymbol{c}_j)$ = the probability density of the detection function evaluated at zero distance for sighting j with associated covariates $\boldsymbol{c}$,

s_j = the number of individuals of the species in the sighting (i.e., species group size), and

N = the number of systematic-effort sightings of the species within the truncation distance.

The inverse of $f(0,\boldsymbol{c}_j)$ is the effective strip width (*ESW*), which is the distance from the trackline beyond which as many sightings were detected as were missed within.

The $g(0)$ estimates used in the present estimation were derived from Beaufort-specific estimates of $g(0)$ (Barlow 2015). The relative values of $g(0)$ from Barlow (2015) were assumed to be absolute values (i.e., $g(0) = 1$ in Beaufort sea state 0) for all sighted taxa, with the exception of Cuvier's beaked whales (*Ziphius cavirostris*), *Mesoplodon* spp., and *Kogia* spp., for which Barlow (2015) provide scaled absolute values of Beaufort-specific $g(0)$ that accounted for availability bias at low Beaufort sea states. Not all HICEAS species were covered in Barlow (2015) because of small sample sizes. For those species, the $g(0)$ estimates of associated species in the detection function species pools were used or averaged as a proxy as in Bradford et al. (2017) with one exception. With the additional line-transect survey effort in the central Pacific since HICEAS 2010, the sample size for pygmy killer whales (*Feresa attenuata*) became sufficient to estimate relative values of Beaufort-specific $g(0)$ for this species using the Barlow (2015) approach. Estimates of $g(0)$ for each species in each survey stratum in each HICEAS year were obtained by taking a weighted average of the Beaufort-specific $g(0)$ values from Barlow (2015), where the weights were the proportion of systematic effort in each Beaufort sea state category (0-6) within each stratum during each HICEAS. Bradford et al. (2017) also used a weighted average of the associated coefficients of variation (CVs) from Barlow (2015), but this approach assumes the Beaufort-specific $g(0)$ values are independent. In the current analysis, the CV for each $g(0)$ weighted average was determined using the Monte Carlo method applied in Moore and Barlow (2017), which approximates the relative $g(0)$ values and associated CVs from Barlow (2015) by a simple exponential function and accounts for the lack of independence in the Beaufort-specific $g(0)$ values.

The abundance of the relevant population for each species was determined by multiplying the density estimate by the area of each survey stratum (minus the area of land masses), which was either the MHI and outer-EEZ stratum for HICEAS 2002 and the Hawaiian EEZ for HICEAS 2010 and HICEAS 2017 (Table A 1). However, the ranges of the pelagic populations of pantropical spotted, spinner (*Stenella longirostris*), and bottlenose dolphins (*Tursiops truncatus*) do not span the entirety of the Hawaiian EEZ (Carretta et al. 2020). Therefore, the area of the ranges of the island-associated population of these species was subtracted from the larger area of each relevant survey stratum (Table A 1). A mixed parametric and nonparametric bootstrap routine was used (n = 1,000 iterations) to estimate the CV for each abundance estimate (Barlow 2006; Barlow and Rankin 2007). Survey effort from all years (1986-2017) was divided into 150-km effort segments, which is the distance generally surveyed in one day. The bootstrap randomly sampled these effort segments with replacement and accounted for the variance associated with sampling variation, modeling the detection function (including model selection and averaging), and uncertainty in the *g*(0) estimate. Uncertainty in *g*(0) was estimated by modeling *g*(0) as a logit-transformed deviate with a mean and variance chosen to give the estimated *g*(0) and CV.

Abundance estimates were determined for all baleen whale species sighted while on systematic effort, with the exception of humpback whales (*Megaptera novaeangliae*) because the nearshore breeding range of this species was insufficiently surveyed during each HICEAS. Abundance estimates were also produced for unidentified cetaceans encountered during each HICEAS, including the following:

- unidentified *Kogia* and *Mesoplodon* spp.;
- unidentified beaked whales;
- rorquals identified as either sei (*Balaenoptera borealis*) or Bryde's (*B. edeni*) whales;
- unidentified rorquals;
- unidentified small, medium, and large dolphins;
- unidentified dolphins;
- unidentified small and large whales;
- unidentified whales; and
- unidentified cetaceans (Table 1).

Sightings of unidentified small, medium, and large dolphins and unidentified dolphins were combined into a single category of "unidentified dolphins" in the estimation. Similarly, sightings of unidentified small and large whales and unidentified whales and cetaceans were combined into an "unidentified cetaceans" category. The treatment of sightings not identified to species when modeling the detection function and applying *g*(0) estimates followed that of Bradford et al. (2017), except that the new *g*(0) for pygmy killer whales was incorporated into the average estimate used for the "unidentified dolphins."

Results

HICEAS Sightings

In total, 231, 379, and 325 cetacean groups were sighted across all effort types during the HICEAS of 2002, 2010, and 2017, respectively. Accounting for mixed-species groups, these group sightings represent 249, 398, and 336 sightings, respectively, of all 24 cetacean species known to regularly occur in the Hawaiian EEZ, although not all species were seen in each year (Table 1). The systematic survey effort relevant to the abundance estimation spanned Beaufort sea states 0–6 (Figure 1), but was largely conducted in Beaufort sea states 3–6 in each HICEAS year (Table A 2–Table A 4). Overall, 148, 198, and 147 cetacean groups were sighted while on systematic survey effort during the HICEAS of 2002, 2010, and 2017, respectively. Factoring in mixed-species groups, these group sightings correspond to 162, 211, and 151 sightings, respectively, of 24 cetacean species and 13 unidentified species categories (Table 1). Systematic-effort sightings were made throughout the Hawaiian EEZ (Figure 1; see Figure B 1–Figure B 8 for species-specific sighting distributions grouped by species pools from Table 2), with most of the sightings of the pelagic populations for species where both are recognized, i.e., pantropical spotted, spinner, and bottlenose dolphins and melon-headed whales (*Peponocephala electra*) (Table 1). Spinner dolphins and dwarf sperm whales (*Kogia sima*) were not sighted on systematic effort during HICEAS 2010 and HICEAS 2017; bottlenose dolphins and sei whales were not sighted on systematic effort during HICEAS 2017; pygmy sperm whales (*K. breviceps*) were not sighted on systematic effort during HICEAS 2010; minke whales were not sighted on systematic effort during HICEAS 2002 and HICEAS 2010; and blue whales (*B. musculus*) were not sighted on systematic effort during HICEAS 2002 and HICEAS 2017.

Of the 70 and 54 systematic-effort sightings of cetaceans initially unidentified to species from 2010 and 2017, respectively, comparisons to the species classification results from available simultaneous acoustic detections (n = 24) only resulted in 7 improvements in species identification, all from HICEAS 2017. Specifically, 2 sightings of unidentified *Mesoplodon* were identified as Blainville's beaked whales (*M. densirostris*); 4 sightings of unidentified beaked whales were identified as sightings of 1 Blainville's, 2 Cuvier's, and 1 Longman's (*Indopacetus pacificus*) beaked whale; and 1 unidentified rorqual sighting was identified as a sei or Bryde's whale (Table 1). Using the 141, 177, and 130 sightings from the HICEAS in 2002, 2010, and 2017, respectively, within the respective truncation distances (N_{EST} in Table 1), abundance in each HICEAS year was estimated for 21 (18 odontocete and 3 mysticetes), 19 (15 odontocetes and 4 mysticetes), and 18 (15 odontocetes and 3 mysticetes) cetacean species, respectively, and for the relevant unidentified species categories. There were 16 species (14 odontocetes, 2 mysticetes) for which abundance was estimated in all HICEAS years (Figure 2).

Line-transect Estimates

Of the 6 covariates of interest, only 4 (*Beaufort*, *group size*, *ship*, and *species*) were tested in the 11 models of detection function, with only *Beaufort* and *group size* tested in all cases (Table 2). Sample sizes were insufficient to test for the effect of *cruise number* and *year* on any of the detection functions. *Group size* and *Beaufort* most frequently contributed to the model-averaged estimates of detection function, with *group size* and *Beaufort* selected in 6 and 5 detection functions, respectively. While species was a consideration for 8 detection functions, this covariate was only tested in 5 cases and selected in 4 (Table 2).

The line-transect parameter estimates of mean *ESW* and *s* vary across species and HICEAS year (Table 3). Mean *ESW* values range from 1.72 to 4.36 km, are generally lowest for the cryptic whale species with small group sizes (multi-species pool 5 in Table 2), and are generally highest for sperm (*Physeter macrocephalus*) and killer (*Orcinus orca*) whales and for the small delphinids with relatively large group sizes (multi-species pool 1 in Table 2). Mean species group sizes range from 1.0 to 382.8 individuals, are lowest for the cryptic whales and rorquals, and are generally highest for the small delphinids. The relative values of Beaufort-specific *g*(0) for pygmy killer whales (Table A 5) are lower than the values for the other delphinids included in Barlow (2015), with the exception of rough-toothed dolphins (*Steno bredanensis*). Given the proportions of systematic survey effort are highest in Beaufort sea states 3-6 (Table A 2–Table A 4), the resulting weighted-average estimates of *g*(0) for each species in each survey stratum in each HICEAS year were relatively low, ranging from <0.01 to 0.64 (Table 3). The estimates are lowest for the cryptic whales and rough-toothed dolphins and highest for sperm, killer, short-finned pilot (*Globicephala macrorhynchus*), and Longman's beaked whales.

The density estimates of all species in each HICEAS year are less than approximately 30 individuals per 1,000 km^2, although almost half of the estimates are less than 2 individuals per 1,000 km^2 (Table 4). Accounting for the estimated density of false killer whales (Bradford et al. 2020), total cetacean density (all species and taxonomic categories combined) during the HICEAS of 2002, 2010, and 2017 was approximately 110, 155, and 160 individuals per 1,000 km^2, respectively. Species abundance point estimates range from 137 blue whales in 2010 to 76,375 rough-toothed dolphins in 2017 (Table 4; Figure 2 and Figure B 9–Figure B 13). The most abundant species during HICEAS 2002 were rough-toothed dolphins, dwarf sperm whales, and striped dolphins (*Stenella coeruleoalba*); during HICEAS 2010 were rough-toothed, striped, and Fraser's (*Lagenodelphis hosei*) dolphins; and during HICEAS 2017 were rough-toothed dolphins, pygmy sperm whales, and Fraser's dolphins. The least abundant species in 2002 were sei, killer, and fin (*Balaenoptera physalus*) whales; in 2010 were blue, killer, and fin whales; and in 2017 were Bryde's, killer, and fin whales. Given the low number of sightings of most species in each year, the CVs for the density and abundance estimates are generally high, ranging from 0.27 to 1.71 (Table 4).

Approximately 2%, 6%, and 18% of the estimated cetacean abundance was not identified to species in 2002, 2010, and 2017, respectively, although most of this abundance is associated with relatively low taxonomic categories. About 1%, 4%, and 4% of the estimated delphinid abundance represents unknown species in 2002, 2010, and 2017, respectively, while 3%, 34%, and 33% of the rorqual abundance and 54%, 42%, and 37% of the beaked whale abundance was not identified to species in each year. *Kogia* spp. were sighted on systematic survey effort only during HICEAS 2002 and HICEAS 2017. All of the kogiid abundance in 2002 was identified to species, while 56% of the abundance in 2017 is of unidentified *Kogia*. The relatively high abundance estimate of unidentified *Kogia* in 2017 (53,421 individuals; Table 4 and Figure B 11D) explains the comparatively high percentage of estimated cetacean abundance unidentified to species in 2017. The estimated abundance of cetaceans with unknown taxonomic status (i.e., "unidentified cetaceans") is relatively low in each year (around 0.1%).

Discussion

The present analysis incorporated cetacean sightings from the HICEAS in 2002, 2010, and 2017 into a unified analytical framework so that the resulting estimates of abundance for each population would be as comparable as possible. However, comparisons between the estimates are still complicated by several factors. Given the low encounter rates in the study area, random variation in the sampling process (e.g., survey conditions) and sighting attributes (e.g., group size) has a strong influence on the data collected and, in turn, the abundance estimated. Such random variation clearly contributed to differences in some point estimates by species (e.g., group sizes of Longman's beaked whales as described in Bradford et al. (2017)) and is also associated with the high variance in the estimates that further obscures detecting any possible trends in abundance. Additionally, interannual variation in environmental and oceanographic conditions can lead to differences in the distribution and density of species in the study area (Forney et al. 2015). Not only does this variation in habitat compound the sampling and sighting variation, but the movement of individuals beyond the jurisdictional boundary of the Hawaiian EEZ would result in abundance estimates that are not reflective of the actual population size. Habitat variation is specifically addressed by model-based abundance estimation, making this method preferred when sample sizes permit.

The abundance estimation framework used in the present analysis incorporated updated data, but was largely the same as that used by Bradford et al. (2017). The updated HICEAS 2010 abundance estimates (Table 4) are strikingly similar to the initial estimates (see Table 3 in Bradford et al. 2017) suggesting robustness of the estimation approach. The two exceptions are the estimates for pygmy killer whales, with a higher updated estimate, and Cuvier's beaked whales, with a lower updated estimate. The difference in the estimates for pygmy killer whales can be attributed to the use of Beaufort-specific $g(0)$ estimates for this species (Table A 5) instead of estimates averaged from other species as a proxy. The weighted-average $g(0)$ estimate of 0.14 (Table 3) applied in the current analysis was much lower than the estimate of 0.31 from Bradford et al. (2017), which largely explains why the point estimate increased from 10,640 to 27,833 individuals in the present estimation while the CV remained consistent. The difference in the estimates for Cuvier's beaked whales is likely a result of a decrease in the truncation distance (from 5.0 to 4.5 km; Table 2) used to estimate the detection function of cryptic whales. The shorter truncation distance eliminated 1 of only 2 systematic-effort sightings of this species in 2010, resulting in a decrease in the updated point estimate (from 723 to 338 individuals) and an increase in the updated CV (from 0.69 to 1.02).

Comparisons to the original abundance estimates associated with HICEAS 2002 (Barlow 2006) are confounded by changes in the estimation framework, primarily the use of the Beaufort-specific $g(0)$ values from Barlow (2015). Barlow (2015) demonstrated that $g(0)$ and thus abundance had previously been substantially underestimated for most species in the eastern and central Pacific. While this work has led to important insights about $g(0)$ for these species, continued analyses would lead to further refinements that could have an impact on future abundance estimates. Such analyses could include accounting for group size in the Beaufort-specific estimates, incorporating availability bias into estimates in calm sea conditions for more species than beaked whales and *Kogia* spp., providing estimates for species currently associated with proxies (e.g., Fraser's dolphins) when sample sizes are sufficient, and using acoustics to inform or validate the estimates (e.g., Rankin et al. 2020). The use of acoustics could potentially be particularly informative for rough-toothed dolphins, which were an outlier among delphinids in Barlow (2015) showing the most rapid decline in *g*(0) with increasing Beaufort sea state. This effect is evident in the elevated abundance estimates for this species (Figure B 9D), which are the highest of all species in each HICEAS year (Figure B 9–Figure B 13). However, the factors contributing to the low *g*(0) estimates are not readily apparent from qualitative comparisons of multispecies data (see Discussion in Bradford et al. 2017).

The precision of the abundance estimates from each HICEAS year is generally poor (Table 4; Figure B 9–Figure B 13). The low numbers of sightings led to a high variance in each encounter rate that dominated the overall CV estimates and resulted in low power to detect trends in abundance during the study period. The abundance estimates from all species had overlapping 95% confidence intervals (CIs), with the exception of Bryde's (Figure B 12E) and Cuvier's beaked (Figure B 11F) whales. For these species, the 95% CIs of the HICEAS 2010 and HICEAS 2017 estimates did not overlap, suggesting a significant difference between the two HICEAS estimates, although this suggestion was not explicitly tested (e.g., Lo 1994). Previous simulation work has shown that random variation in the encounter rate of pelagic false killer whales can at least partially explain the observed variation in the resulting design-based abundance estimates (Bradford et al. 2020). However, the false killer whale abundance estimates from the HICEAS of 2002, 2010, and 2017 all had overlapping 95% CIs, warranting an evaluation of the role of random variation in the encounter rate of Bryde's and Cuvier's beaked whales.

Consequently, a post-hoc simulation study was conducted to examine whether the difference in the 2010 and 2017 encounter rates of these two species (Table 1) could have occurred by chance if the overall abundance of each population did not change during that time (Appendix C). While this study found that the observed encounter rates could have occurred by chance given constant abundance, the estimated probabilities were rather low, especially for Bryde's whales. This finding indicates that other factors are likely contributing to the estimates, including shifts in distribution in and out of the Hawaiian EEZ or actual changes in population abundance. Bryde's whales were among the nine species included in the model-based estimation of abundance for each HICEAS year (Becker et al. In Review). The model-based point estimates of Bryde's whale abundance did decrease between 2010 and 2017, suggesting movement out of the study area in 2017. But the decrease was only by about 150 individuals (compared to the design-based decrease of approximately 1,650 individuals), and the associated 95% CIs overlapped. The model-based estimation of Becker et al. (In Review) was constrained in testing for temporal trends, so an underlying assumption of the analysis is that there are no changes in abundance aside from those predicted by the selected habitat covariates. While the design-based estimation is often dominated by the influence of sampling and sighting variation, in this case, it identifies the possibility that unmeasured factors, habitat or otherwise, led to a significant reduction in Bryde's whale abundance in 2017. Although the design-based results are also suggestive of a significant increase in Cuvier's beaked whale abundance in 2017, this possibility is more difficult to interpret given the somewhat higher simulated probabilities (Appendix C) and the lack of inference from a model-based estimation.

Random variation in encounter rate can likely also explain why some species were not sighted while on systematic survey effort in a given HICEAS year (Table 1), particularly for cryptic species with low encounter rates (e.g., *Kogia* spp.). The possibility that it may also explain or at least contribute to a lack of systematic-effort sightings of a more detectable species (e.g., bottlenose dolphins in 2017; Table 1) underscores the impact of encounter rate variation on the assessment of cetaceans in the Hawaiian EEZ. Without at least one systematic-effort sighting during a survey, an associated abundance estimate cannot be produced for use in the SAR or other assessment contexts. Although bottlenose dolphins were included in the model-based abundance estimation (Becker et al. In Review), the resulting estimates are not differentiated by population, as there were not sufficient sightings of the pelagic population to build a robust population-specific model. Thus, an abundance estimate for 2017 is not available for bottlenose dolphins or for spinner dolphins and dwarf sperm, sei, and blue whales.

Beyond the enhanced productivity associated with the Hawaiian Islands, the waters of the broader EEZ are generally oligotrophic, which is reflected in the low densities of cetaceans compared to more productive regions (e.g., Barlow and Forney 2007; Wade and Gerrodette 1993). Averaging across the estimates from each HICEAS year, approximately 81% of the estimated cetacean density in the Hawaiian EEZ consists of dolphin species, followed by about 14% *Kogia* spp., 3% beaked whales, and 2% large whales (i.e., sperm and baleen whales). Dolphin density is underestimated because it does not account for the island-associated populations of pantropical spotted, spinner, and bottlenose dolphins and melon-headed whales or the population of false killer whales in the MHI. However, while current abundance estimates do not exist for most of these populations (Carretta et al. 2020), available estimates for Hawaii Island spinner dolphins (Tyne et al. 2016) and MHI Insular false killer whales (Bradford et al. 2018) suggest that the island-associated populations are appreciably smaller than their pelagic counterparts. While the density of dolphins does currently account for at least some portion of insular individuals from species with putative island-associated populations (e.g., rough-toothed dolphins and short-finned pilot whales; Albertson et al. 2017; Van Cise et al. 2017), the underlying estimates will need to be reevaluated if additional island-associated populations are recognized (Oleson et al. 2013).

Given that the encounter rates of the long-diving cryptic whales (i.e., *Kogia* spp. and beaked whales) are consistently among the lowest measured, a greater emphasis was placed during HICEAS 2017 on using acoustic methods (specifically drifting acoustic recorders, see Yano et al. 2018) to detect these species and ultimately estimate their abundance, offering a valuable point of comparison to the present estimates. The density of the seasonally migrating species of baleen whales (i.e., minke, sei, fin, and blue whales) is underestimated because the HICEAS surveys were conducted during the summer and fall. The recently completed winter HICEAS of 2020 will allow for the abundance estimation of some migrating baleen whale species, including humpback whales, during the winter period of their peak abundance. The species-specific abundance estimates that will be incorporated into the SARs and potentially applied to other assessment efforts do not include an appreciable abundance associated with unidentified species, particularly for rorquals, beaked whales, and *Kogia* spp. Future efforts to refine the HICEAS abundance estimates could include the use of a proration approach (e.g., Wade and Gerrodette 1993) to assign the abundance of unidentified cetaceans to species. The design-based estimation presented here offers the most comprehensive evaluation to date of the abundance of the 24 cetacean species that regularly occur in the Hawaiian EEZ. Additional studies, including habitat-based modeling, satellite tagging, photo-identification, acoustic analyses, and simulation approaches, can provide additional temporal and spatial inference that may be required for assessment and management of high priority species.

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Tables

Table 1. Names and number of sightings of cetacean species and taxonomic categories visually observed in the U.S. Hawaiian Islands Exclusive Economic Zone (EEZ) during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) in 2002, 2010, and 2017. Table continues on following page, and notes follow end of table.

			2002					2010			2017		
Common name	Scientific name	Population name	N_{TOT}	N_{SYS}	N_{EST}	$N_{EST\text{-}MHI}$	$N_{EST\text{-}EEZ}$	N_{TOT}	N_{SYS}	N_{EST}	N_{TOT}	N_{SYS}	N_{EST}
Pantropical spotted dolphin	*Stenella attenuata*	Hawaii Pelagic	5	3	3	1	2	12	11	10	14	10	8
Pantropical spotted dolphin	*Stenella attenuata*	Oahu	2	1	-	-	-	0	0	-	0	0	-
Pantropical spotted dolphin	*Stenella attenuata*	4-Islands	1	1	-	-	-	0	0	-	2	0	-
Pantropical spotted dolphin	*Stenella attenuata*	Hawaii Island	5	3	-	-	-	0	0	-	9	0	-
Striped dolphin	*Stenella coeruleoalba*	Hawaii	15	11	11	1	10	25	20	19	20	17	16
Spinner dolphin	*Stenella longirostris*	Hawaii Pelagic	7	5	5	3	2	0	0	-	0	0	-
Spinner dolphin	*Stenella longirostris*	Midway Atoll/Kure	0	0	-	-	-	2	0	-	1	0	-
Spinner dolphin	*Stenella longirostris*	Kauai/Niihau	0	0	-	-	-	2	0	-	0	0	-
Spinner dolphin	*Stenella longirostris*	Oahu/4-islands	1	0	-	-	-	0	0	-	1	0	-
Spinner dolphin	*Stenella longirostris*	Hawaii Island	0	0	-	-	-	0	0	-	1	0	-
Rough-toothed dolphin	*Steno bredanensis*	Hawaii	18	14	14	7	7	24	8	8	25	9	8
Bottlenose dolphin	*Tursiops truncatus*	Hawaii Pelagic	9	8	8	4	4	16	7	6	2	0	-
Bottlenose dolphin	*Tursiops truncatus*	Kauai/Niihau	0	0	-	-	-	2	0	-	0	0	-
Bottlenose dolphin	*Tursiops truncatus*	Oahu	4	0	-	-	-	0	0	-	0	0	-
Bottlenose dolphin	*Tursiops truncatus*	4-Islands	1	0	-	-	-	0	0	-	2	0	-
Bottlenose dolphin	*Tursiops truncatus*	Hawaii Island	1	1	-	-	-	1	0	-	0	0	-
Risso's dolphin	*Grampus griseus*	Hawaii	7	5	5	2	3	10	9	9	11	6	6
Fraser's dolphin	*Lagenodelphis hosei*	Hawaii	2	2	1	-	1	4	3	3	3	2	2
Melon-headed whale	*Peponocephala electra*	Hawaiian Islands	1	1	1	-	1	1	1	1	6	3	3
Melon-headed whale	*Peponocephala electra*	Kohala Resident	0	0	-	-	-	0	0	-	1	0	-
Pygmy killer whale	*Feresa attenuata*	Hawaii	3	2	2	2	-	5	4	4	3	2	2
False killer whale[1]	*Pseudorca crassidens*	Hawaii Pelagic, NWHI, MHI	2	1	1	-	1	14	6	6	26	9	7
Short-finned pilot whale	*Globicephala macrorhynchus*	Hawaii	25	16	16	8	8	36	15	11	35	5	5
Killer whale	*Orcinus orca*	Hawaii	2	2	2	-	2	1	1	1	1	1	1
Sperm whale	*Physeter macrocephalus*	Hawaii	45	28	21	4	17	41	26	23	23	14	12
Pygmy sperm whale	*Kogia breviceps*	Hawaii	2	2	2	-	2	0	0	-	3	3	3

			2002					2010			2017		
Common name	**Scientific name**	**Population name**	N_{TOT}	N_{SYS}	N_{EST}	$N_{EST\text{-}MHI}$	$N_{EST\text{-}EEZ}$	N_{TOT}	N_{SYS}	N_{EST}	N_{TOT}	N_{SYS}	N_{EST}
Dwarf sperm whale	*Kogia sima*	Hawaii	5	3	3	-	3	1	0	-	0	0	-
Unidentified *Kogia*	*Kogia sima/breviceps*	-	1	0	-	-	-	1	0	-	5	3	3
Blainville's beaked whale	*Mesoplodon densirostris*	Hawaii	3	1	1	-	1	2	1	1	11	3	2
Cuvier's beaked whale	*Ziphius cavirostris*	Hawaii	4	3	2	-	2	23	2	1	13	8	7
Longman's beaked whale	*Indopacetus pacificus*	Hawaii	1	1	1	-	1	3	3	3	8	5	4
Unidentified *Mesoplodon*	*Mesoplodon* spp.	-	4	4	4	-	4	10	6	6	5	3	3
Unidentified beaked whale	Ziphiid whale	-	3	2	2	1	1	27	4	3	18	5	5
Minke whale	*Balaenoptera acutorostrata*	Hawaii	1	0	-	-	-	1	0	-	1	1	1
Bryde's whale	*Balaenoptera edeni*	Hawaii	14	10	9	-	9	32	19	19	2	2	2
Sei whale	*Balaenoptera borealis*	Hawaii	6	4	3	3	-	2	2	2	0	0	-
Fin whale	*Balaenoptera physalus*	Hawaii	5	2	2	-	2	2	1	1	2	1	1
Blue whale	*Balaenoptera musculus*	Western North Pacific	0	0	-	-	-	1	1	1	0	0	-
Humpback whale	*Megaptera novaeangliae*	Central North Pacific	1	1	-	-	-	1	1	-	6	2	-
Sei or Bryde's whale	*Balaenoptera borealis/edeni*	-	0	0	-	-	-	12	9	8	5	2	2
Unidentified rorqual	Balaenopterid whale	-	2	1	1	-	1	11	9	6	6	4	4
Unidentified small dolphin	Small delphinid	-	8	3	3	-	3	17	10	6	20	7	5
Unidentified medium dolphin	Medium delphinid	-	1	1	1	1	-	6	3	1	8	3	3
Unidentified large dolphin	Large delphinid	-	1	1	1	-	1	3	2	2	0	0	-
Unidentified dolphin	Delphinid	-	13	8	5	3	2	19	9	6	17	11	9
Unidentified small whale	Small whale or large dolphin	-	6	4	4	-	4	1	1	1	5	3	3
Unidentified large whale	Large baleen or sperm whale	-	4	2	2	1	1	8	6	-	8	3	1
Unidentified whale	Small or large whale	-	4	3	3	-	3	3	2	2	3	2	-
Unidentified cetacean	Cetacean	-	4	2	2	1	1	16	9	7	4	2	2

[1]Abundance estimation of false killer whale populations is covered in Bradford et al. (2020) for the Hawaii Pelagic and Northwestern Hawaiian Islands (NWHI) populations and Bradford et al. (2018) for the main Hawaiian Islands (MHI) Insular population.

Population names refer to those used in the NOAA Fisheries Stock Assessment Reports (e.g., Carretta et al. 2020). N_{TOT} = the number of sightings across all effort types; N_{SYS} = the number of sightings made while on systematic effort in Beaufort sea states 0–6; and N_{EST} = the number of sightings made while on systematic effort that were within the analytical truncation distance and, therefore, used in the line-transect abundance estimation, shown also by MHI ($N_{EST\text{-}MHI}$) and outer-EEZ ($N_{EST\text{-}EEZ}$) stratum for HICEAS 2002. The abundance of some species could not be estimated (-). Numbers of sightings for HICEAS 2010 are shaded gray for visual clarity. Numbers of sightings for HICEAS 2017 reflect improvements in species identification (n = 7) following classification of acoustic data.

Table 2. Detection functions modeled by using pooled sightings collected in the central Pacific during line-transect surveys conducted in 1986-2017 by the NOAA Fisheries Southwest and Pacific Islands Fisheries Science Centers. Table continues on following page, and notes follow end of table.

Detection function	N_{TOT}	N_{DET}	TD	Covariates tested	Best-fit model
Pantropical spotted dolphin	320	298	5.0	*Beaufort*, *group size*, *ship*, *species*	*Group size*+*ship*+*species*
Pantropical spotted dolphin	234	218			
Other	86	80			
Spinner dolphin	248	228	5.0	*Beaufort*, *group size*, *species*	*Group size*
Spinner dolphin	174	158			
Other	74	70			
Multi-species pool 1	336	310	5.0	*Beaufort*, *group size*, *ship*, *species*	*Beaufort*+*ship*(+*species*)
Striped dolphin	290	269			
Fraser's dolphin	26	25			
Melon-headed whale	17	16			
Other[1]	3	0			
Multi-species pool 2	293	275	5.0	*Beaufort*, *group size*, *species*	*Group size*+*species*
Rough-toothed dolphin	77	73			
Bottlenose dolphin	74	68			
Risso's dolphin	77	74			
Pygmy killer whale	18	18			
Other	47	42			
Multi-species pool 3	214	201	5.0	*Beaufort*, *group size*	Null(+*Beaufort*)
Short-finned pilot whale	193	183			
Longman's beaked whale	10	9			
Other	11	9			
Multi-species pool 4	200	168	5.5	*Beaufort*, *group size*, *species*	Null(+*species*)
Killer whale	39	37			
Sperm whale	159	131			
Other[1]	2	0			

Detection function	N_{TOT}	N_{DET}	TD	Covariates tested	Best-fit model
Multi-species pool 5	234	221	4.5	*Beaufort*, *group size*	*Group size*
Pygmy sperm whale	5	5			
Dwarf sperm whale	26	26			
Unidentified *Kogia*	7	7			
Blainville's beaked whale	15	14			
Cuvier's beaked whale	61	55			
Unidentified *Mesoplodon*	49	49			
Unidentified beaked whale	66	60			
Minke whale	2	2			
Other	3	3			
Multi-species pool 6	160	146	5.0	*Beaufort*, *group size*	Null(+*Beaufort*)
Bryde's whale	84	79			
Sei whale	11	9			
Fin whale	6	6			
Blue whale	4	4			
Sei or Bryde's whale	49	43			
Other	6	5			
Unidentified rorquals	73	53	5.5	*Beaufort*, *group size*	Null
Unidentified dolphin	400	329	5.5	*Beaufort*, *group size*, *ship*	*Beaufort*+*group size*
Unidentified cetacean	195	156	5.5	*Beaufort*, *group size*	Null(+*Beaufort*)(+*group size*)

[1]The "other" sightings in this pool were within the truncation distance (TD) but were removed for other reasons as explained in text.

Left-justified entries in the first column are the detection functions estimated; indented entries are the factor levels for the *species* covariate, with the "other" factor level representing mixed-species sightings for which the most abundant species was not one of the pooled species. N_{TOT} is the number of available systematic- and nonsystematic-effort sightings in Beaufort sea states 0–6, and N_{DET} is the number of sightings that fell within the analytical TD (in km). If a model with an additional covariate was within 2 AICc units of the best-fit covariate model, the second covariate is shown in parentheses.

Table 3. Estimates of line-transect parameters for cetacean species and taxonomic categories sighted while on systematic survey effort during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) in 2002, 2010, and 2017. Table continues on following page, and notes follow end of table.

	2002 – MHI			2002 – outer-EEZ			2010			2017		
Species or category	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**
Pantropical spotted dolphin	3.08	68.1	0.29 (0.11)	3.15	85.6	0.29 (0.11)	2.30	43.2	0.28 (0.12)	2.71	56.5	0.26 (0.12)
Striped dolphin	2.14	54.9	0.34 (0.19)	2.92	40.4	0.36 (0.18)	3.74	51.1	0.33 (0.20)	3.99	36.3	0.32 (0.21)
Spinner dolphin	2.22	58.4	0.25 (0.11)	1.89	31.7	0.29 (0.11)	-	-	-	-	-	-
Rough-toothed dolphin	2.46	15.7	0.09 (0.45)	2.56	19.3	0.09 (0.45)	2.67	25.3	0.08 (0.48)	2.33	25.0	0.08 (0.50)
Bottlenose dolphin	2.35	6.0	0.26 (0.34)	2.54	19.8	0.28 (0.34)	2.35	33.5	0.27 (0.35)	-	-	-
Risso's dolphin	2.33	15.0	0.59 (0.17)	3.00	21.0	0.58 (0.18)	2.71	26.6	0.58 (0.18)	2.38	18.9	0.55 (0.20)
Fraser's dolphin	-	-	-	3.04	382.8	0.36 (0.18)	3.63	283.3	0.33 (0.20)	4.00	359.6	0.32 (0.21)
Melon-headed whale	-	-	-	3.04	119.2	0.36 (0.18)	4.02	153.0	0.33 (0.20)	3.26	187.9	0.32 (0.21)
Pygmy killer whale	1.83	17.8	0.15 (0.24)	-	-	-	1.94	25.7	0.14 (0.27)	1.76	14.6	0.12 (0.28)
Short-finned pilot whale	3.24	35.1	0.61 (0.14)	3.23	21.3	0.60 (0.15)	3.24	40.9	0.60 (0.16)	3.24	37.5	0.55 (0.17)
Killer whale	-	-	-	3.97	7.4	0.62 (0.37)	3.97	4.7	0.62 (0.38)	3.97	4.9	0.58 (0.42)
Sperm whale	4.36	3.9	0.64 (0.33)	4.36	9.8	0.64 (0.33)	4.36	7.4	0.64 (0.33)	4.36	15.2	0.62 (0.35)
Pygmy sperm whale	-	-	-	1.72	1.0	0.008 (0.13)	-	-	-	1.87	1.4	0.004 (0.15)
Dwarf sperm whale	-	-	-	2.23	2.7	0.008 (0.13)	-	-	-	-	-	-
Unidentified *Kogia*	-	-	-	-	-	-	-	-	-	2.01	2.0	0.004 (0.15)
Blainville's beaked whale	-	-	-	2.23	2.7	0.12 (0.27)	2.77	7.0	0.11 (0.29)	1.94	1.7	0.11 (0.29)
Cuvier's beaked whale	-	-	-	2.05	2.3	0.14 (0.28)	1.72	1.0	0.13 (0.29)	2.01	2.2	0.12 (0.30)
Longman's beaked whale	-	-	-	3.24	20.4	0.60 (0.15)	3.23	59.8	0.60 (0.16)	3.23	15.0	0.55 (0.17)
Unidentified *Mesoplodon*	-	-	-	2.10	2.3	0.12 (0.27)	2.06	2.2	0.11 (0.29)	2.27	3.5	0.11 (0.29)
Unidentified beaked whale	1.72	1.0	0.13 (0.19)	1.72	1.0	0.13 (0.20)	2.21	3.1	0.12 (0.21)	1.72	1.0	0.12 (0.21)
Minke whale	-	-	-	-	-	-	-	-	-	1.72	1.0	0.10 (1.03)
Bryde's whale	-	-	-	2.94	1.7	0.42 (0.20)	2.81	1.4	0.41 (0.20)	2.79	1.7	0.39 (0.21)
Sei whale	2.83	3.3	0.42 (0.20)	-	-	-	2.79	3.1	0.41 (0.20)	-	-	-
Fin whale	-	-	-	2.83	3.0	0.34 (0.26)	2.83	2.0	0.34 (0.27)	2.75	2.3	0.31 (0.28)
Blue whale	-	-	-	-	-	-	2.83	2.8	0.55 (0.34)	-	-	-
Sei or Bryde's whale	-	-	-	-	-	-	2.87	1.5	0.41 (0.20)	2.83	1.2	0.39 (0.21)
Unidentified rorqual	-	-	-	4.16	1.0	0.36 (0.17)	4.16	1.6	0.35 (0.17)	4.16	1.0	0.33 (0.19)

	2002 – MHI			2002 – outer-EEZ			2010			2017		
Species or category	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**
Unidentified dolphin	3.24	4.3	0.34 (0.08)	2.96	4.2	0.33 (0.08)	3.34	15.2	0.33 (0.08)	3.13	8.5	0.30 (0.09)
Unidentified cetacean	2.73	1.0	1.00 (NA)	2.64	1.0	1.00 (NA)	2.82	2.0	1.00 (NA)	2.85	1.2	1.00 (NA)

A main Hawaiian Islands (MHI) stratum was sampled more intensively within the U.S. Hawaiian Islands Exclusive Economic Zone (EEZ) in 2002. Mean effective strip width (*ESW*) is the average *ESW* of the sightings used in the abundance estimation (N_{EST} in Table 1), was computed from the covariates associated with each sighting, and represents the distance from the trackline (in km) beyond which as many sightings were made as were missed within. Mean species group size (*s*) is the average estimated sighting group size calibrated and proportioned to species of the N_{EST} sightings. The probabilities of detection on the trackline (*g*(0)) were derived from Barlow (2015) as described in the text; the coefficients of variation (CV) for the *g*(0) estimates are included in parentheses. Estimates for HICEAS 2010 are shaded gray for visual clarity.

Table 4. Estimates of density (individuals per 1,000 km^2) and abundance for cetacean species and taxonomic categories sighted while on systematic survey effort during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) in 2002, 2010, and 2017. Table continues on following page, and notes follow end of table.

	2002				2010				2017			
Species or category	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**
Pantropical spotted dolphin	7.08	16,931	0.65	5,289-54,202	20.68	49,488	0.39	23,551-103,992	16.63	39,798	0.51	15,432-102,637
Striped dolphin	13.85	33,896	0.40	15,826-72,600	24.93	61,029	0.35	31,113-119,708	14.00	34,271	0.32	18,481-63,552
Spinner dolphin	7.43	16,562	0.62	5,435-50,470	-	-	-	-	-	-	-	-
Rough-toothed dolphin	26.95	65,959	0.39	31,344-138,803	30.23	74,001	0.39	35,197-155,586	31.20	76,375	0.41	35,286-165,309
Bottlenose dolphin	3.99	9,678	0.49	3,924-23,868	10.38	25,188	0.58	8,791-72,168	-	-	-	-
Risso’s dolphin	1.64	4,003	0.64	1,279-12,528	4.48	10,957	0.43	4,879-24,609	2.55	6,245	0.50	2,481-15,718
Fraser’s dolphin	11.84	28,980	1.02	5,518-152,195	23.16	56,688	0.70	16,391-196,056	16.73	40,960	0.70	11,887-141,143
Melon-headed whale	3.69	9,024	1.08	1,602-50,821	3.57	8,743	1.01	1,685-45,375	16.61	40,647	0.74	11,097-148,890
Pygmy killer whale	1.57	3,854	0.77	1,015-14,640	11.37	27,833	0.50	10,950-70,747	4.22	10,328	0.75	2,771-38,491
False killer whale – Pelagic[1]	0.25	613	1.2	96-3,906	1.02	2,489	0.74	678-9,143	2.09	5,106	0.63	1,640-15,892
False killer whale – NWHI[1]	-	-	-	-	1.95	878	1.15	145-5,329	1.06	477	1.71	48-4,712
Short-finned pilot whale	4.73	11,566	0.34	6,054-22,098	7.18	17,583	0.42	8,014-38,576	3.25	7,956	0.59	2,720-23,268
Killer whale	0.20	499	0.90	111-2,245	0.06	145	0.98	29-726	0.07	161	1.06	29-881
Sperm whale	2.09	5,114	0.96	1,043-25,060	1.89	4,617	0.31	2,542-8,387	2.08	5,095	0.56	1,822-14,249
Pygmy sperm whale	4.92	12,036	1.04	2,248-64,434	-	-	-	-	17.19	42,083	0.64	13,406-132,103
Dwarf sperm whale	15.30	37,440	0.78	9,758-143,648	-	-	-	-	-	-	-	-
Unidentified *Kogia*	-	-	-	-	-	-	-	-	21.83	53,421	0.63	17,083-167,056
Blainville’s beaked whale	0.34	839	1.05	155-4,536	0.71	1,740	1.05	320-9,468	0.46	1,132	0.99	224-5,731
Cuvier’s beaked whale	0.50	1,216	0.77	319-4,633	0.14	338	1.02	65-1,771	1.81	4,431	0.41	2,036-9,644
Longman’s beaked whale	0.36	871	1.06	158-4,798	2.86	7,003	0.63	2,260-21,697	1.04	2,550	0.67	771-8,432
Unidentified *Mesoplodon*	1.18	2,897	0.57	1,032-8,135	1.70	4,168	0.47	1,742-9,972	1.19	2,923	0.61	978-8,734
Unidentified beaked whale	0.21	504	0.79	128-1,980	1.01	2,465	0.73	689-8,814	0.75	1,826	0.46	773-4,313
Minke whale	-	-	-	-	-	-	-	-	0.18	438	1.05	81-2,372
Bryde’s whale	0.43	1,043	0.37	521-2,086	0.73	1,794	0.29	1,035-3,109	0.06	139	0.72	39-492
Sei whale	0.10	253	0.76	68-947	0.16	401	0.84	95-1,685	-	-	-	-
Fin whale	0.21	509	0.73	141-1,842	0.06	158	1.07	29-871	0.08	203	0.99	40-1,028
Blue whale	-	-	-	-	0.06	137	1.12	23-796	-	-	-	-

	2002				2010				2017			
Species or category	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**
Sei or Bryde's whale	-	-	-	-	0.32	786	0.45	338-1,832	0.06	157	0.71	45-548
Unidentified rorqual	0.02	55	1.01	11-286	0.21	506	0.47	212-1,206	0.09	220	0.53	83-585
Unidentified dolphin	1.09	2,676	0.43	1,191-6,012	6.34	15,511	0.33	8,319-28,921	4.88	11,952	0.38	5,858-24,386
Unidentified cetacean	0.13	308	0.45	132-720	0.22	540	0.50	212-1,373	0.08	197	0.45	85-456

[1]Abundance estimation of the Hawaii Pelagic and Northwestern Hawaiian Islands (NWHI) false killer whale populations is covered in (Bradford et al. 2020), but the resulting design-based estimates are reported here for completeness.

The coefficients of variation (CV) apply to estimates of both density and abundance. Log-normal 95% confidence intervals (CIs) for the abundance estimates are shown. Stratum-specific estimates for relevant species and categories from HICEAS 2002 can be found in Table A 6. Estimates for HICEAS 2010 are shaded gray for visual clarity.

Figures

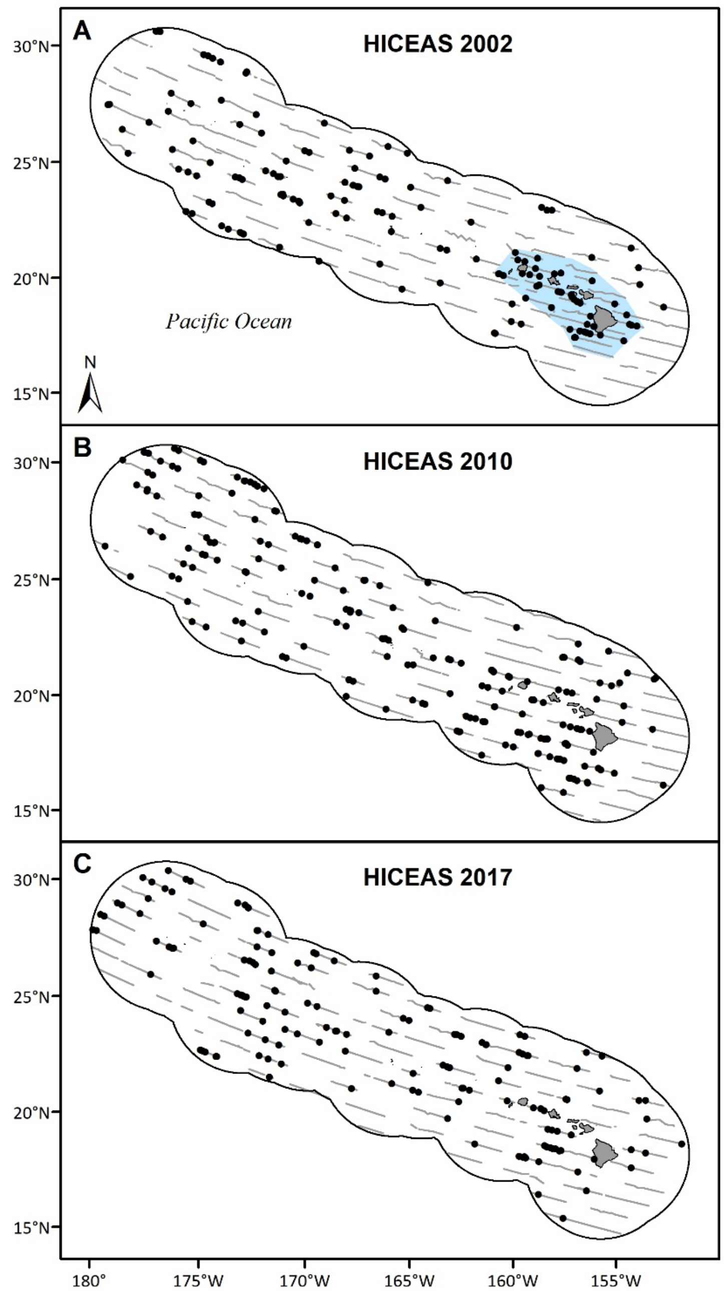

Figure 1. Locations of cetacean groups (black dots; n = 493) sighted during systematic line-transect survey effort (fine lines) in Beaufort sea states 0−6 within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002 (n = 148), (B) 2010 (n = 198), and (C) 2017 (n = 147).

A total of 27 sightings across all years were of mixed-species groups, in which at least 2 species were seen. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

Figure 2. Heat map showing point estimates of abundance for cetacean species (n = 23) during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

Species are listed in order of highest (blue shading) to lowest (yellow shading) average abundance. The point estimates shown for false killer whales are for the pelagic population. Full abundance estimates for all species and taxonomic categories are listed in Table 4 and shown in Figure B 9–Figure B 13.

Appendix A: Supplementary Tables

Table A 1. Survey strata area values (km^2) used to scale the line-transect density estimates to abundance for the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) of 2002, 2010, and 2017.

Species	MHI (2002)	Outer-EEZ (2002)	Hawaiian EEZ (2010, 2017)
Pantropical spotted dolphin	157,397	2,235,180	2,392,576
Spinner dolphin	181,423	2,229,552	-
Bottlenose dolphin	190,616	2,235,180	2,425,795
All others	212,455	2,235,180	2,447,635

A main Hawaiian Islands (MHI) stratum was sampled more intensively within the U.S. Exclusive Economic Zone of the Hawaiian Islands (Hawaiian EEZ) in 2002. The stratum-specific area values for pantropical spotted, spinner, and bottlenose dolphins are specific to the pelagic populations, which do not span the entirety of the Hawaiian EEZ. Spinner dolphins were not sighted on systematic survey effort during HICEAS 2010 and HICEAS 2017. Bottlenose dolphins were not sighted on systematic survey effort during HICEAS 2017.

Table A 2. Systematic survey effort in total (km) and proportionally by Beaufort (B) sea state within the U.S. Hawaiian Islands Exclusive Economic Zone (Hawaiian EEZ) during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey of 2002.

Species	Stratum	Effort	B0	B1	B2	B3	B4	B5	B6
Pantropical spotted dolphin	MHI	2,527	0.000	0.000	0.140	0.090	0.386	0.304	0.080
Spinner dolphin	MHI	3,064	0.000	0.003	0.097	0.074	0.349	0.290	0.052
Bottlenose dolphin	MHI	3,282	0.000	0.004	0.113	0.075	0.358	0.315	0.063
All others	MHI	3,540	0.000	0.004	0.135	0.085	0.376	0.334	0.066
All species	Outer-EEZ	13,473	0.008	0.015	0.045	0.100	0.491	0.311	0.030

A main Hawaiian Islands (MHI) stratum was sampled more intensively within the Hawaiian EEZ in 2002. While effort in the outer-EEZ stratum was applicable to all species, effort in the MHI was adjusted to account for the ranges of the pelagic populations of pantropical spotted, spinner, and bottlenose dolphins.

Table A 3. Systematic survey effort in total (km) and proportionally by Beaufort (B) sea state within the U.S. Hawaiian Islands Exclusive Economic Zone (Hawaiian EEZ) during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey of 2010.

Species	Effort	B0	B1	B2	B3	B4	B5	B6
Pantropical spotted dolphin	15,747	0.001	0.012	0.041	0.124	0.474	0.301	0.046
Bottlenose dolphin	16,100	0.001	0.012	0.042	0.122	0.472	0.303	0.046
All others	16,145	0.001	0.012	0.042	0.122	0.473	0.304	0.046

Effort in the Hawaiian EEZ was adjusted to account for the ranges of the pelagic populations of pantropical spotted and bottlenose dolphins.

Table A 4. Systematic survey effort in total (km) and proportionally by Beaufort (B) sea state within the U.S. Hawaiian Islands Exclusive Economic Zone (Hawaiian EEZ) during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey of 2017.

Species	Effort	B0	B1	B2	B3	B4	B5	B6
Pantropical spotted dolphin	15,968	0.001	0.010	0.043	0.122	0.314	0.343	0.167
All others	16,212	0.001	0.009	0.043	0.122	0.316	0.344	0.165

Effort in the Hawaiian EEZ was adjusted to account for the range of the pelagic population of pantropical spotted dolphins.

Table A 5. Relative values of *g*(0) and associated estimates of effective strip width (*ESW*; in km) for pygmy killer whales in Beaufort sea states (B) 0-6 along with the sample size (n) of sightings used in the estimation approach (Barlow 2015).

Parameter	B0	B1	B2	B3	B4	B5	B6
n	5	13	18	16	14	6	1
g(0)	1.00	1.00	0.49	0.24	0.12	0.06	0.03
g(0) CV	0.00	0.00	0.16	0.25	0.34	0.43	0.53
ESW	2.82	2.53	2.26	2.02	1.80	1.60	1.43
ESW CV	0.25	0.17	0.10	0.11	0.19	0.27	0.36

Detection probabilities in Beaufort states of 0 and 1 are assumed to be certain ($g(0) = 1$), and relative probabilities in other conditions are estimated from a model that assumes that true group densities are independent of Beaufort when time and location effects are removed (Barlow 2015). Coefficients of variation (CV) are included for each Beaufort-specific parameter estimate.

Table A 6. Stratum-specific estimates of density (individuals per 1,000 km^2) and abundance for cetacean species and taxonomic categories sighted while on systematic survey effort during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002.

	MHI				Outer-EEZ			
Species or category	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**
Pantropical spotted dolphin	15.07	2,372	1.01	456-12,338	6.51	14,559	0.74	4,000-52,988
Striped dolphin	10.64	2,260	1.06	411-12,436	14.15	31,636	0.43	14,213-70,419
Spinner dolphin	44.94	8153	0.93	1,726-38,507	3.77	8409	0.81	2,084-33,934
Rough-toothed dolphin	67.07	14,250	0.57	5,032-40,356	23.13	51,709	0.48	21,292-125,577
Bottlenose dolphin	6.65	1,267	0.63	409-3,929	3.76	8,411	0.55	3,065-23,084
Risso’s dolphin	3.01	640	0.75	174-2,353	1.51	3,363	0.74	918-12,325
Fraser’s dolphin	-	-	-	-	12.97	28,980	1.02	5,518-152,195
Melon-headed whale	-	-	-	-	4.04	9,024	1.08	1,602-50,821
Pygmy killer whale	18.14	3,854	0.77	1,015-14,640	-	-	-	-
False killer whale – Pelagic[1]	-	-	-	-	0.27	613	1.2	96–3,906
Short-finned pilot whale	20.11	4,272	0.47	1,776-10,273	3.26	7,294	0.46	3,078-17,283
Killer whale	-	-	-	-	0.22	499	0.90	111-2,245
Sperm whale	0.79	169	0.64	54-528	2.21	4,945	1.00	970-25,197
Pygmy sperm whale	-	-	-	-	5.39	12,036	1.04	2,248-64,434
Dwarf sperm whale	-	-	-	-	16.75	37,440	0.78	9,758-143,648
Blainville’s beaked whale	-	-	-	-	0.38	839	1.05	155-4,536
Cuvier’s beaked whale	-	-	-	-	0.54	1,216	0.77	319-4,633
Longman’s beaked whale	-	-	-	-	0.39	871	1.06	158-4,798
Unidentified Mesoplodon	-	-	-	-	1.30	2,897	0.57	1,032-8,135
Unidentified beaked whale	0.63	134	1.01	26-691	0.17	370	1.02	71-1,928
Bryde’s whale	-	-	-	-	0.47	1,043	0.37	521-2,086
Sei whale	1.19	253	0.76	68-947	-	-	-	-
Fin whale	-	-	-	-	0.23	509	0.73	141-1,842
Unidentified rorqual	-	-	-	-	0.02	55	1.01	11-286
Unidentified dolphin	2.08	442	0.56	159-1,225	1.00	2,234	0.50	878-5,682
Unidentified cetacean	0.10	22	0.71	6-78	0.13	286	0.49	116-705

[1]Abundance estimation of the Hawaii Pelagic false killer whale population is covered in (Bradford et al. 2020), but the resulting design-based estimates are reported here for completeness.

A main Hawaiian Islands (MHI) stratum was sampled more intensively within the U.S. Hawaiian Islands Exclusive Economic Zone (EEZ) in 2002. The coefficients of variation (CV) apply to estimates of both density and abundance. Log-normal 95% confidence intervals (CIs) for the abundance estimates are shown.

Appendix B: Supplementary Figures

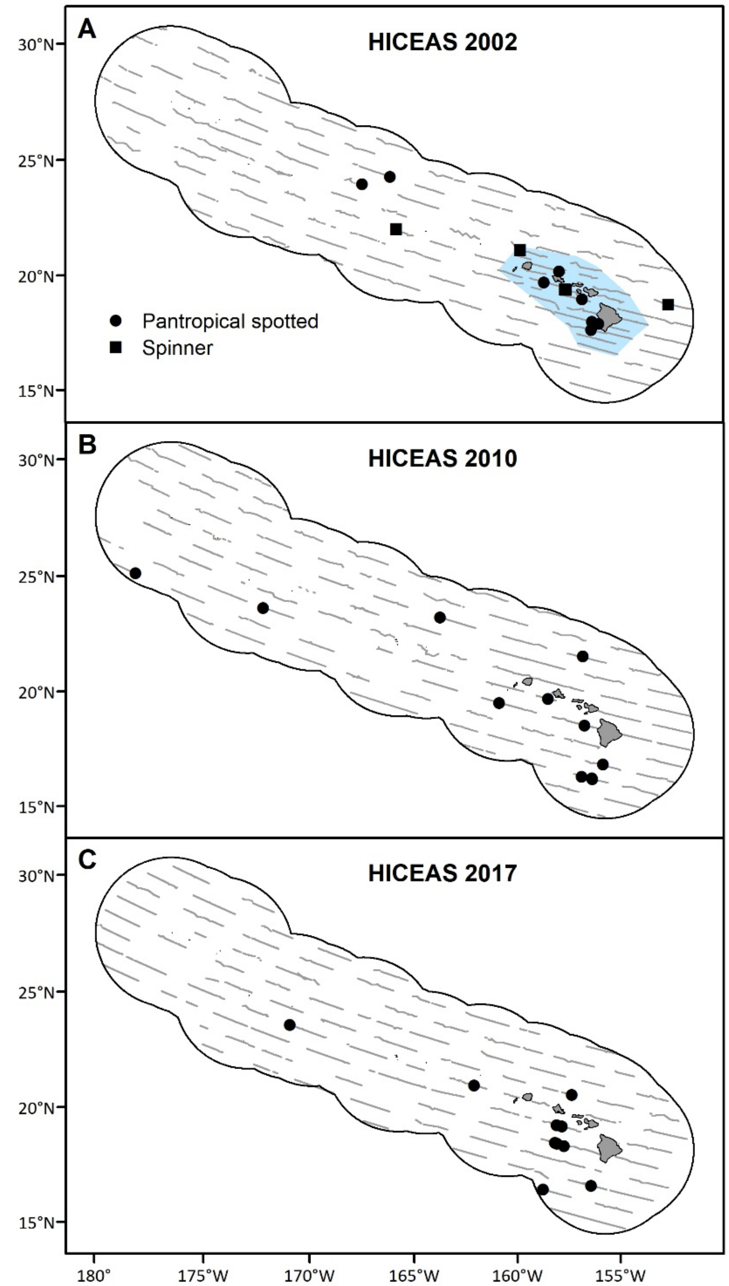

Figure B 1. Locations of pantropical spotted and spinner dolphin sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years, although spinner dolphins were not sighted on systematic effort during HICEAS 2010 and 2017. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

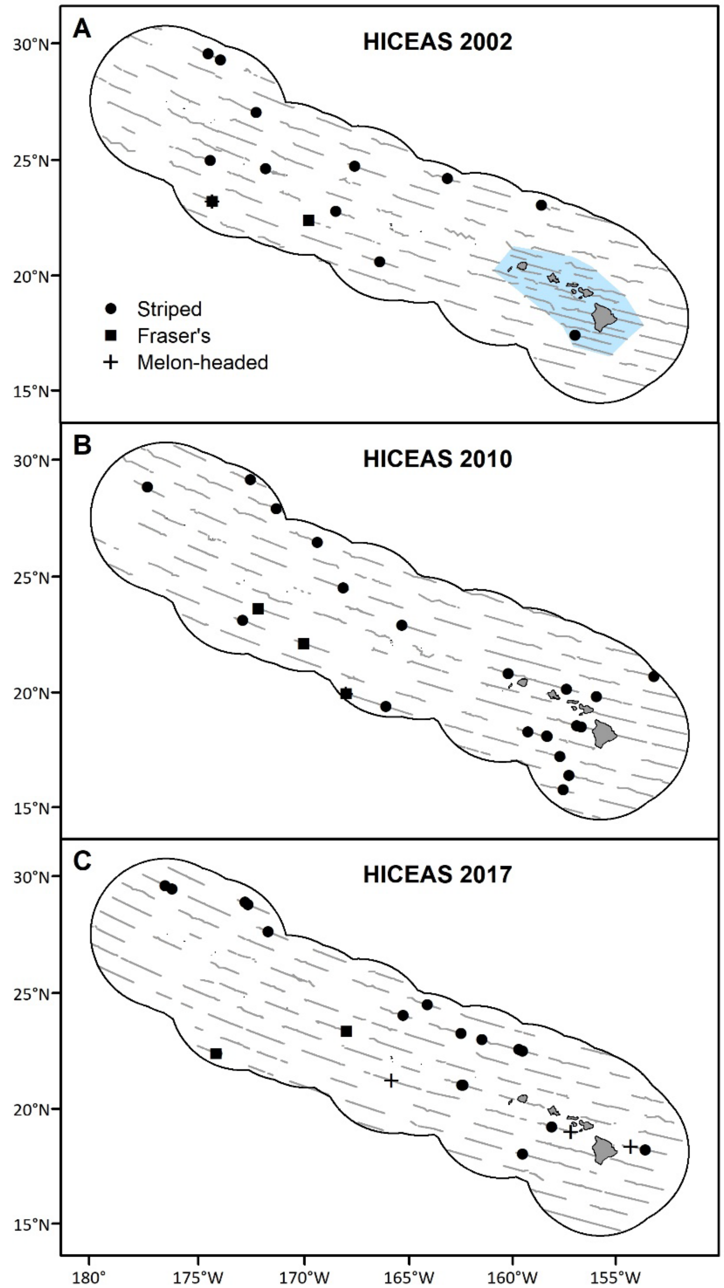

Figure B 2. Locations of striped and Fraser's dolphin and melon-headed whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

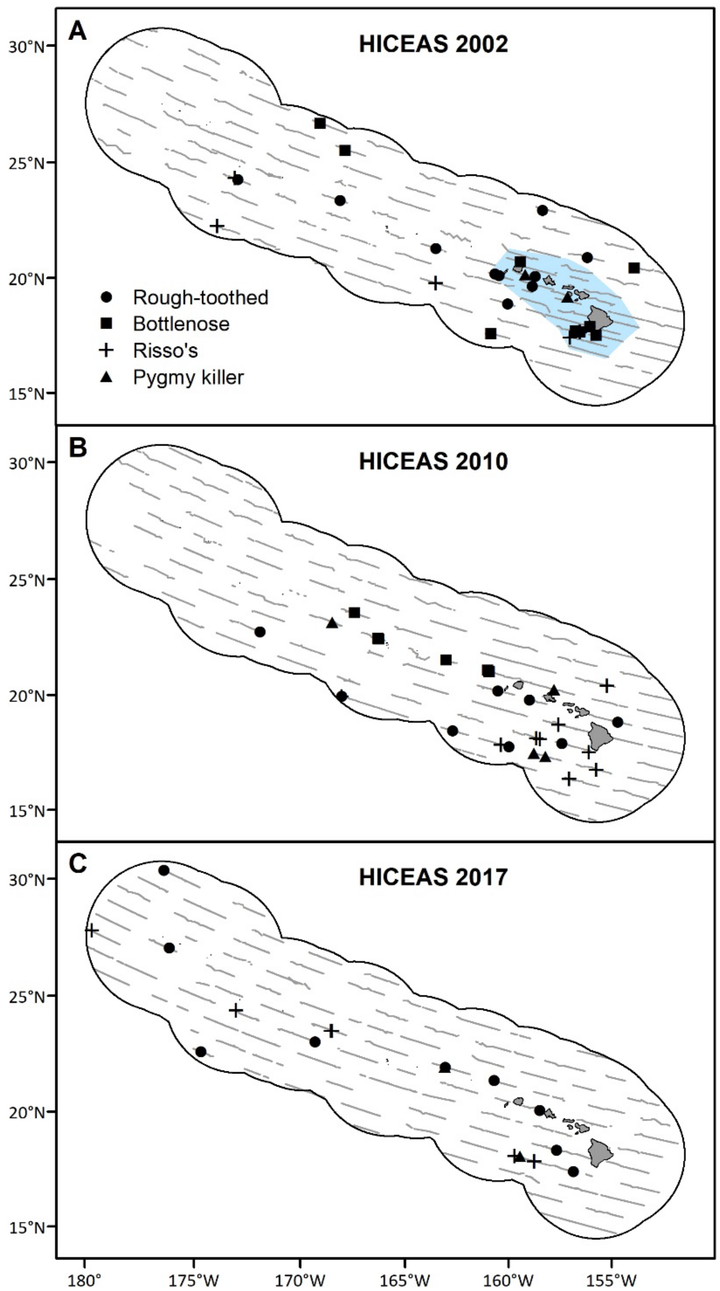

Figure B 3. Locations of rough-toothed, bottlenose, and Risso's dolphin and pygmy killer whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years, although bottlenose dolphins were not sighted on systematic effort during HICEAS 2017. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

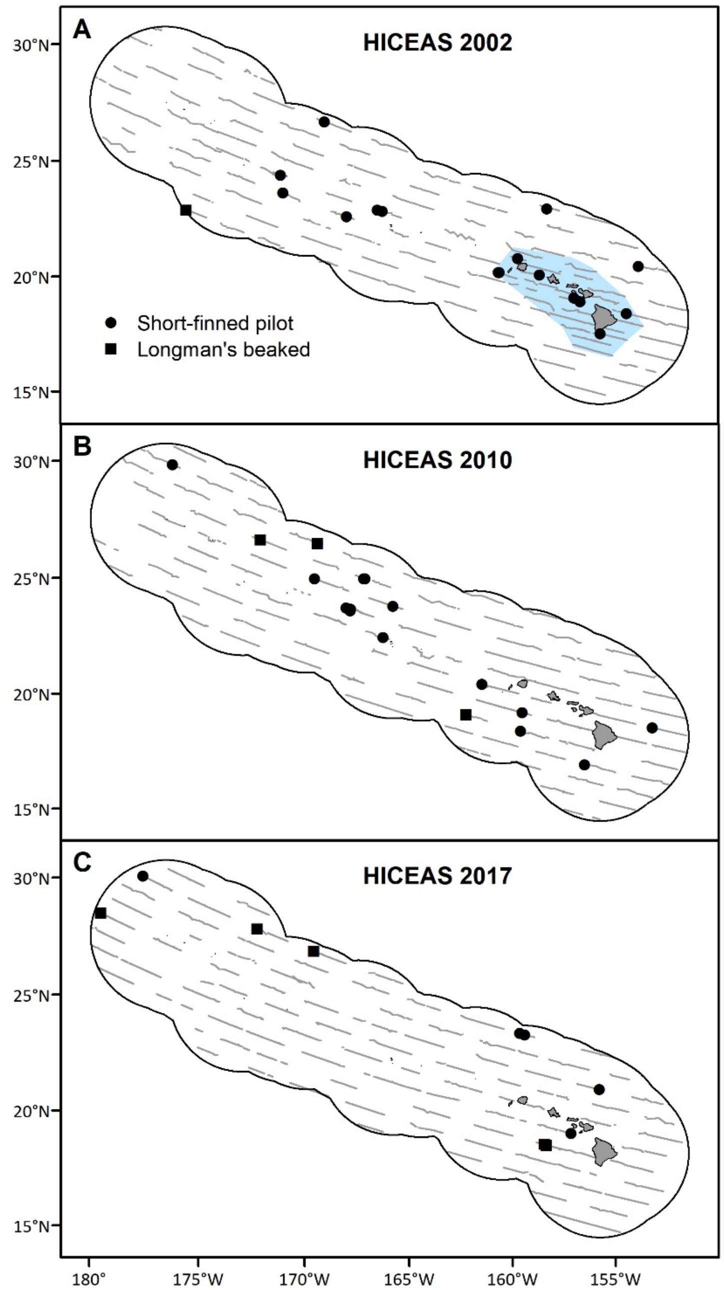

Figure B 4. Locations of short-finned pilot and Longman's beaked whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

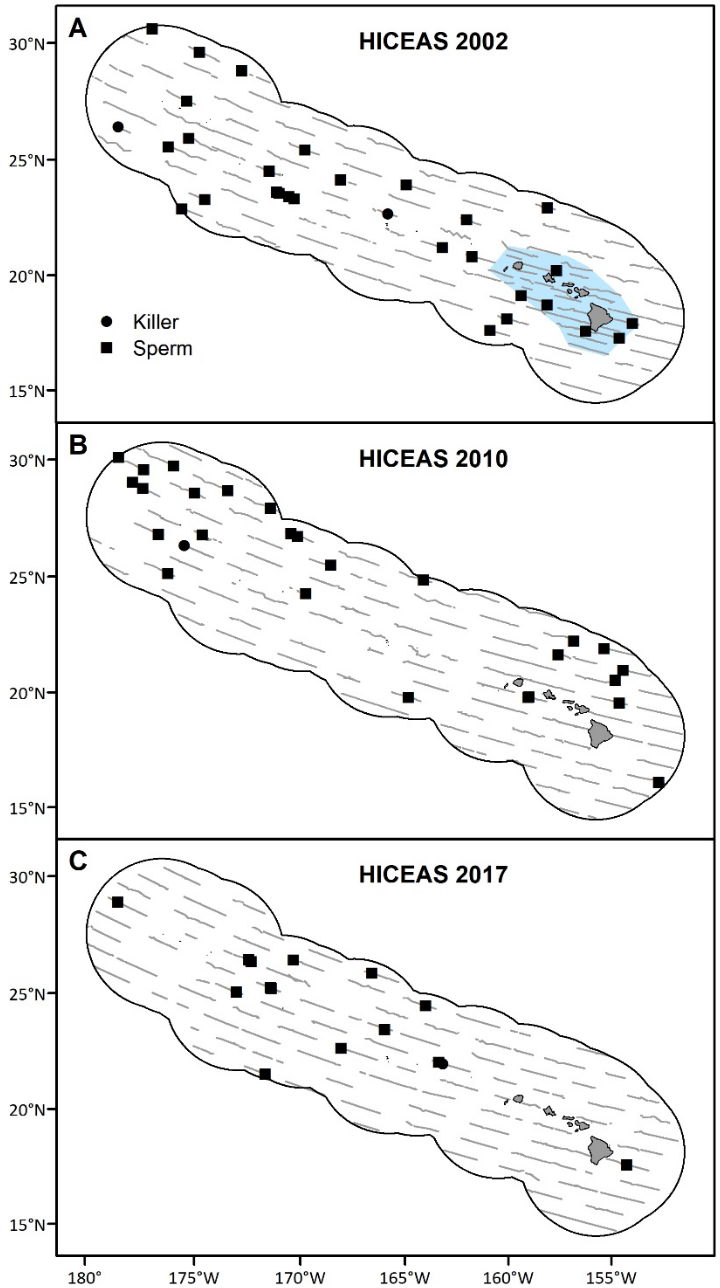

Figure B 5. Locations of killer and sperm whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

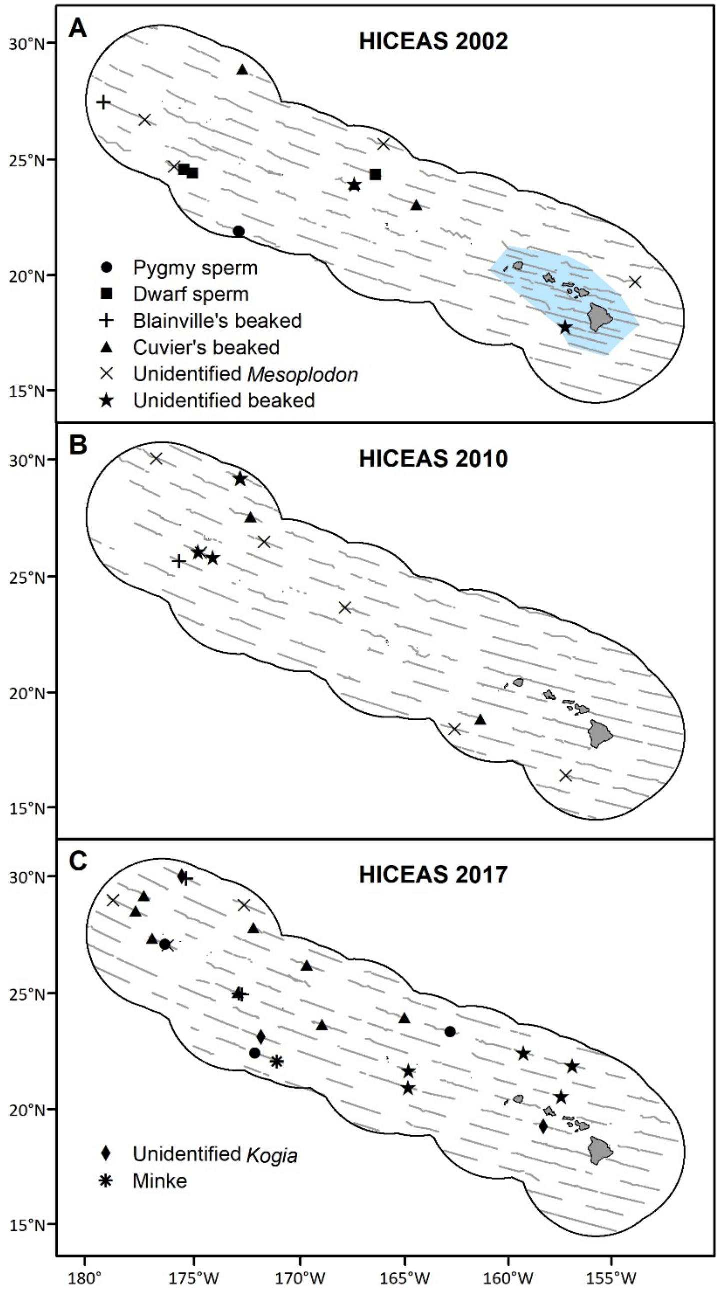

Figure B 6. Locations of pygmy sperm, dwarf sperm, Blainville's beaked, Cuvier's beaked, and minke whale and unidentified *Kogia*, *Mesoplodon*, and beaked whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years, although pygmy sperm whales were not sighted on systematic effort during HICEAS 2010, nor dwarf sperm whales during HICEAS 2010 and 2017. Legend in (C) applies only to HICEAS 2017. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

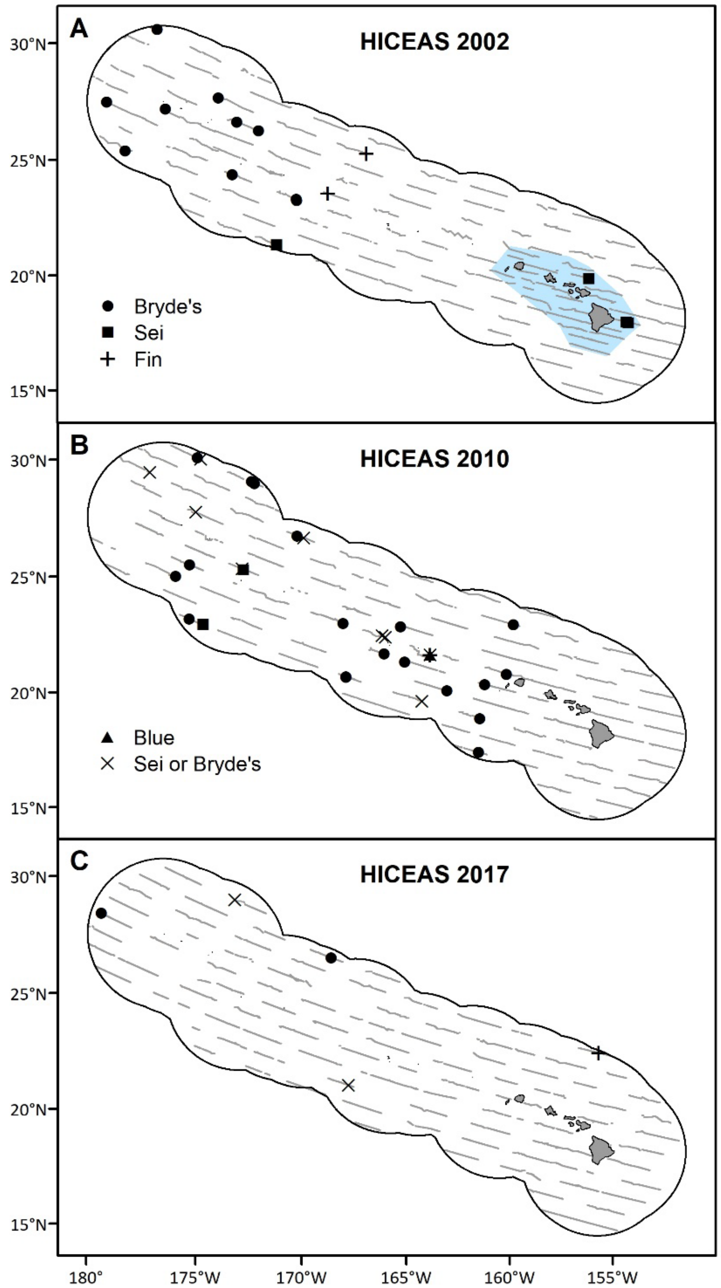

Figure B 7. Locations of Bryde's, Sei, fin, blue, and Sei or Bryde's whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years. Legend in (B) applies to HICEAS 2010 and 2017, although blue whales were not sighted on systematic effort during HICEAS 2017. See N_{SYS} columns in Table 1 for species-specific sample sizes from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

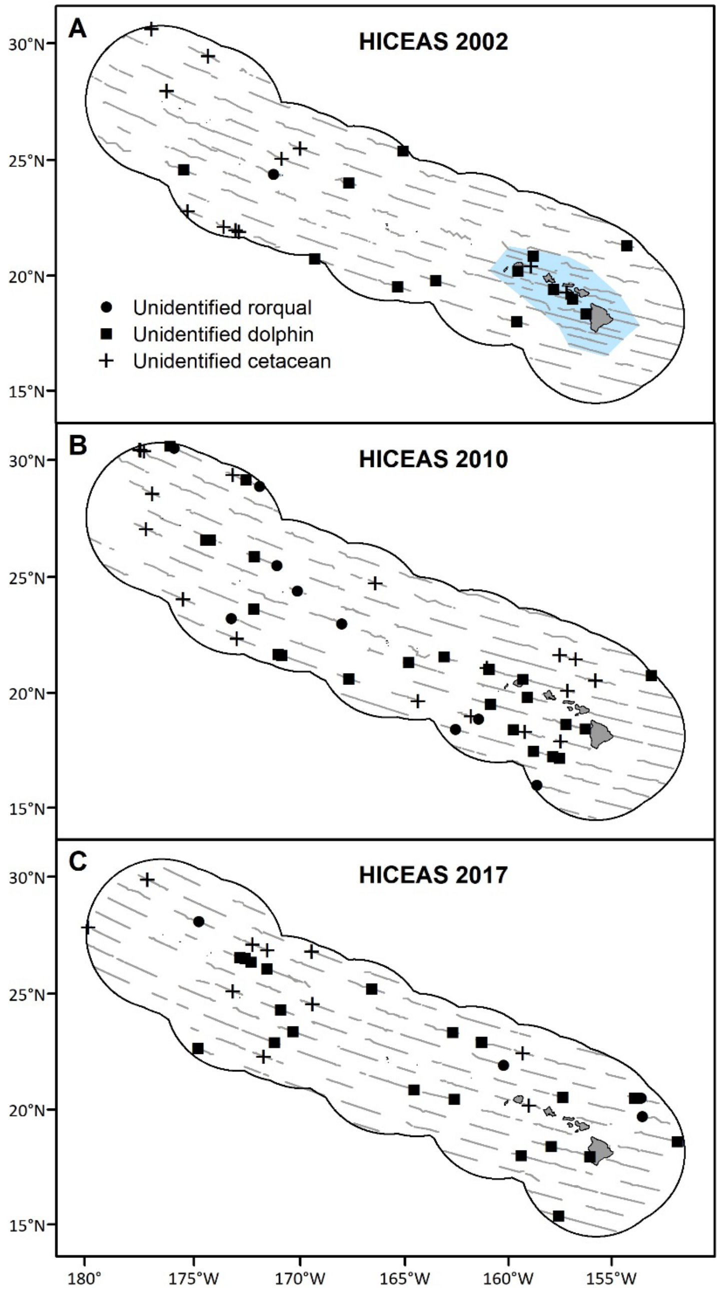

Figure B 8. Locations of unidentified rorqual, dolphin, and whale sightings made on systematic line-transect survey effort (fine lines) within the U.S. Hawaiian Islands Exclusive Economic Zone (black outline) during the Hawaiian Islands Cetacean Ecosystem and Assessment Survey (HICEAS) in (A) 2002, (B) 2010, and (C) 2017.

Legend in (A) applies to all HICEAS years. See N_{SYS} columns in Table 1 for sample sizes by taxonomic category from each year. The light blue polygon represents the main Hawaiian Islands (MHI) survey stratum used during HICEAS 2002. The MHI are shown in gray with a thin black outline.

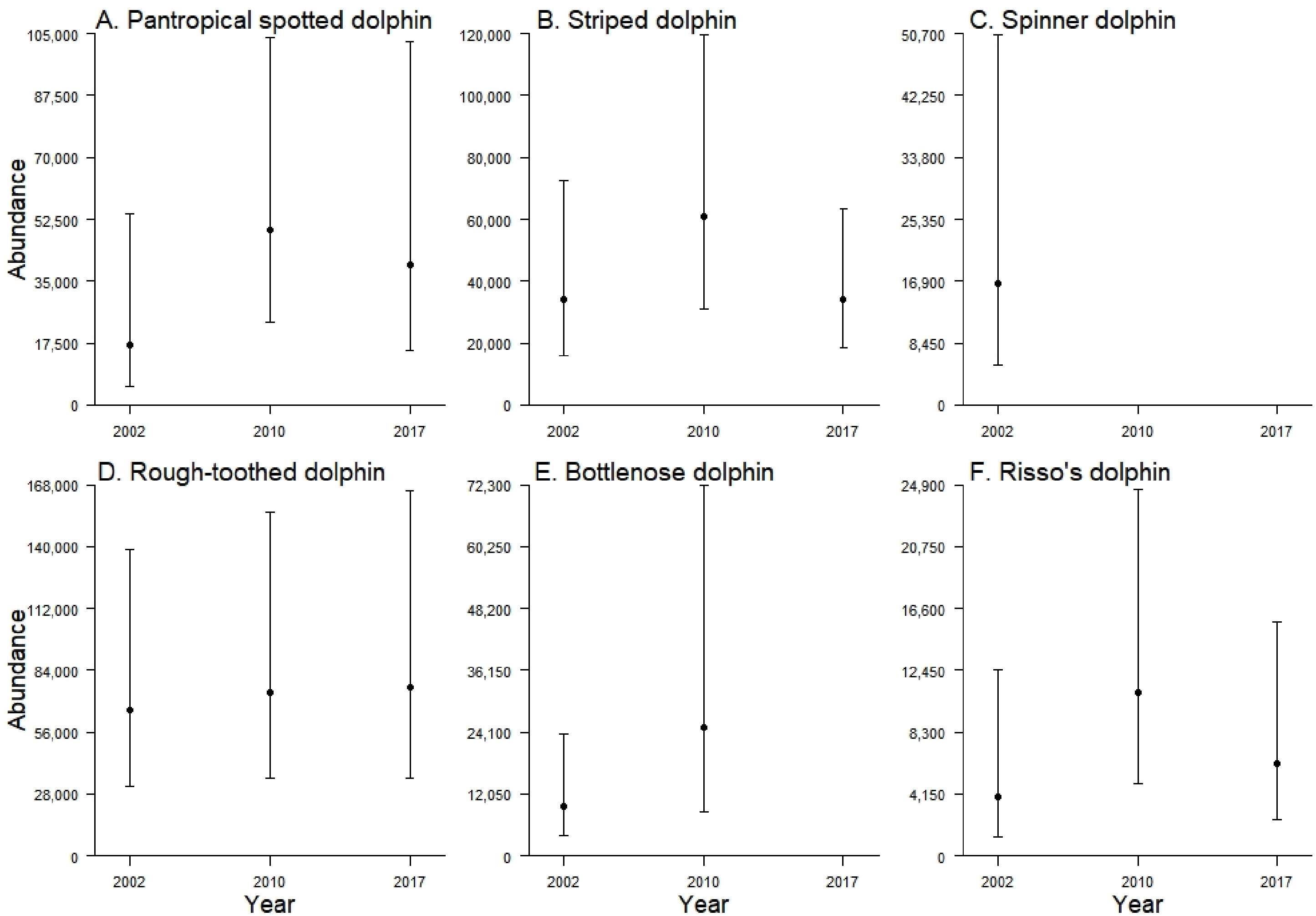

Figure B 9. Estimated abundance (with 95% confidence intervals) of (A) pantropical spotted, (B) striped, (C) spinner, (D) rough-toothed, (E) bottlenose, and (F) Risso's dolphins during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

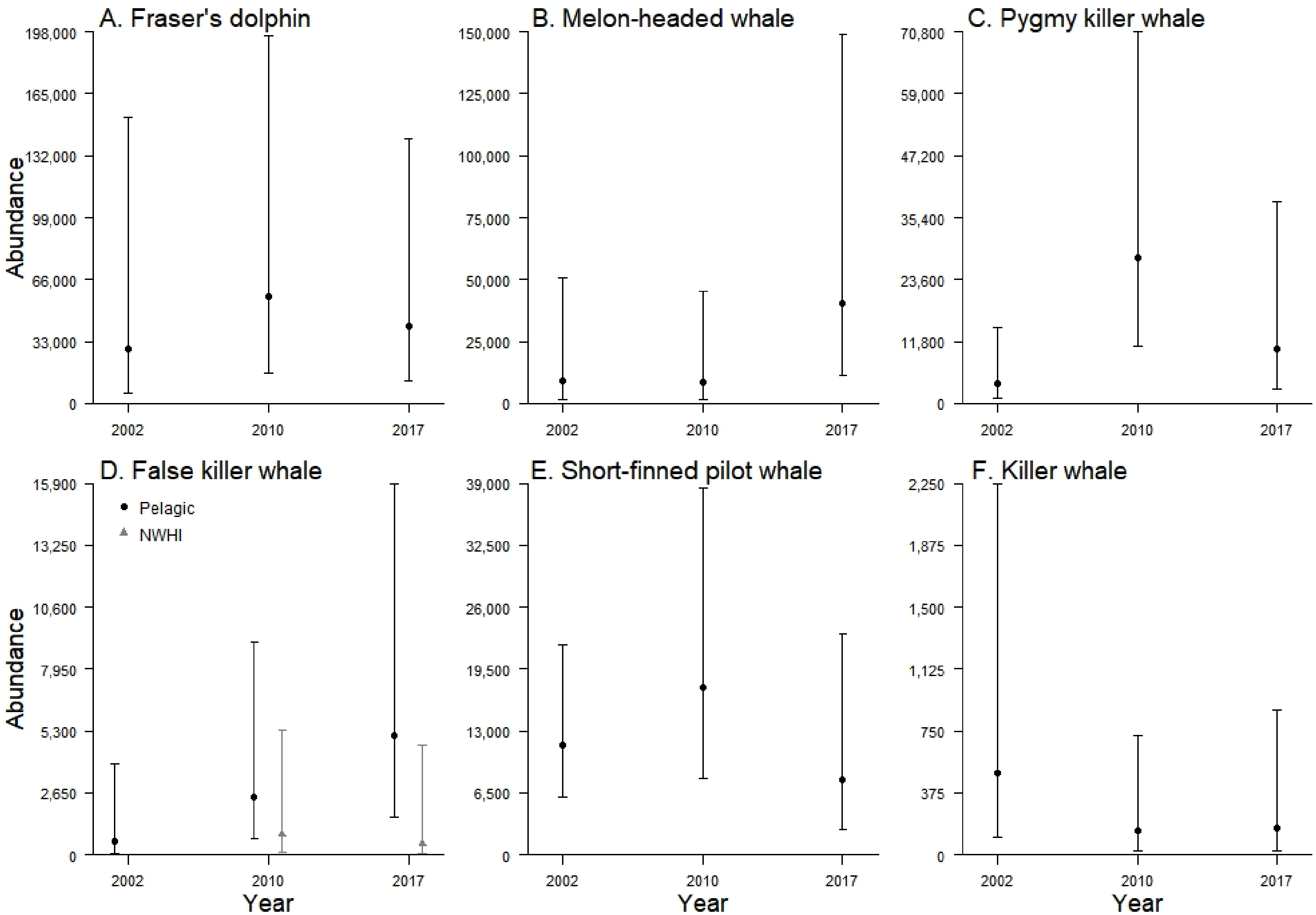

Figure B 10. Estimated abundance (with 95% confidence intervals) of (A) Fraser's dolphins and (B) melon-headed, (C) pygmy killer, (D) false killer (Hawaii Pelagic and Northwestern Hawaiian Islands, NWHI, populations), (E) short-finned pilot, and (F) killer whales during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

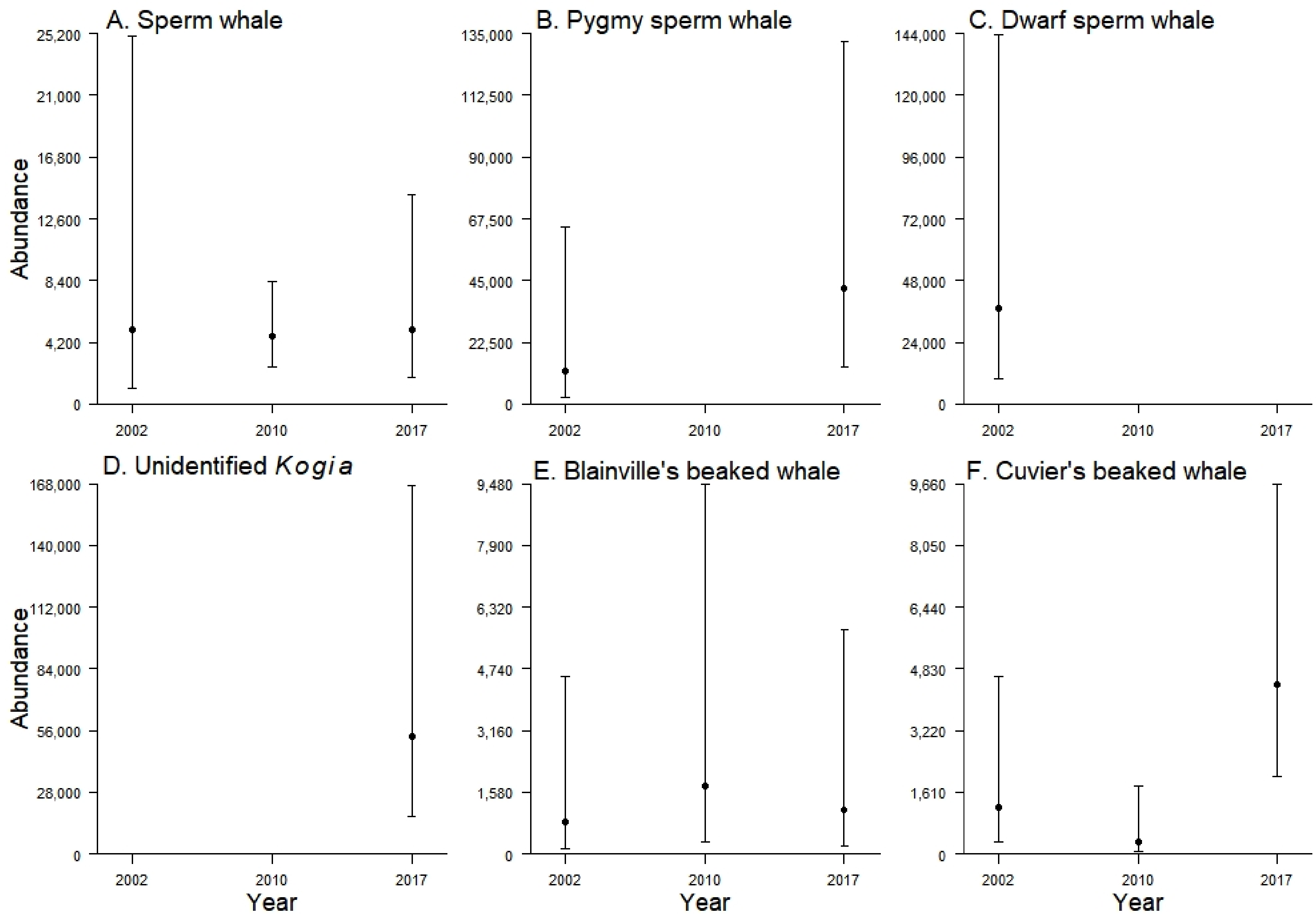

Figure B 11. Estimated abundance (with 95% confidence intervals) of (A) sperm, (B) pygmy sperm, (C) dwarf sperm, (D) unidentified *Kogia*, (E) Blainville's beaked, and (F) Cuvier's beaked whales during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

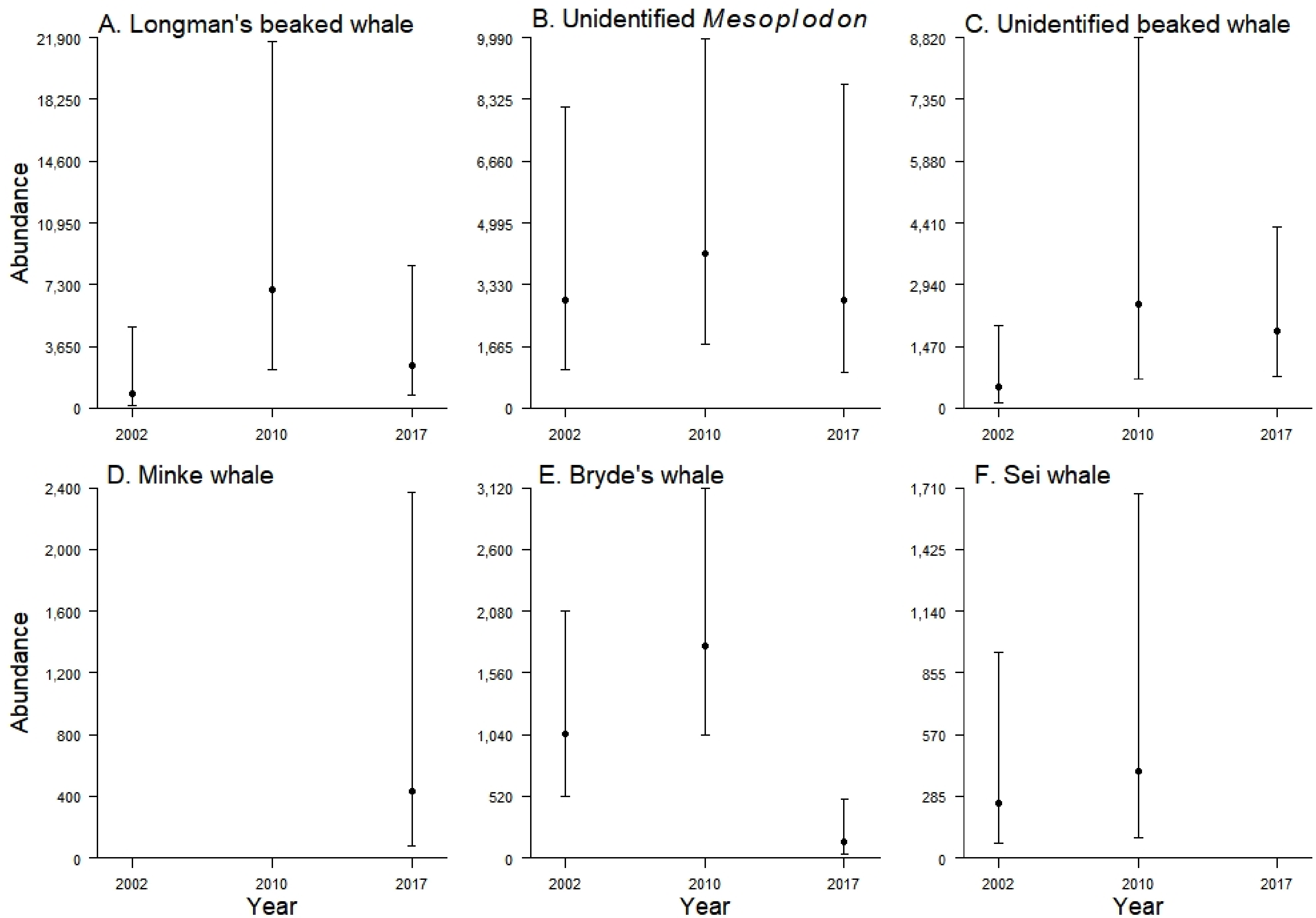

Figure B 12. Estimated abundance (with 95% confidence intervals) of (A) Longman's beaked, (B) unidentified *Mesoplodon*, (C) unidentified beaked, (D) minke, (E) Bryde's, and (F) sei whales during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

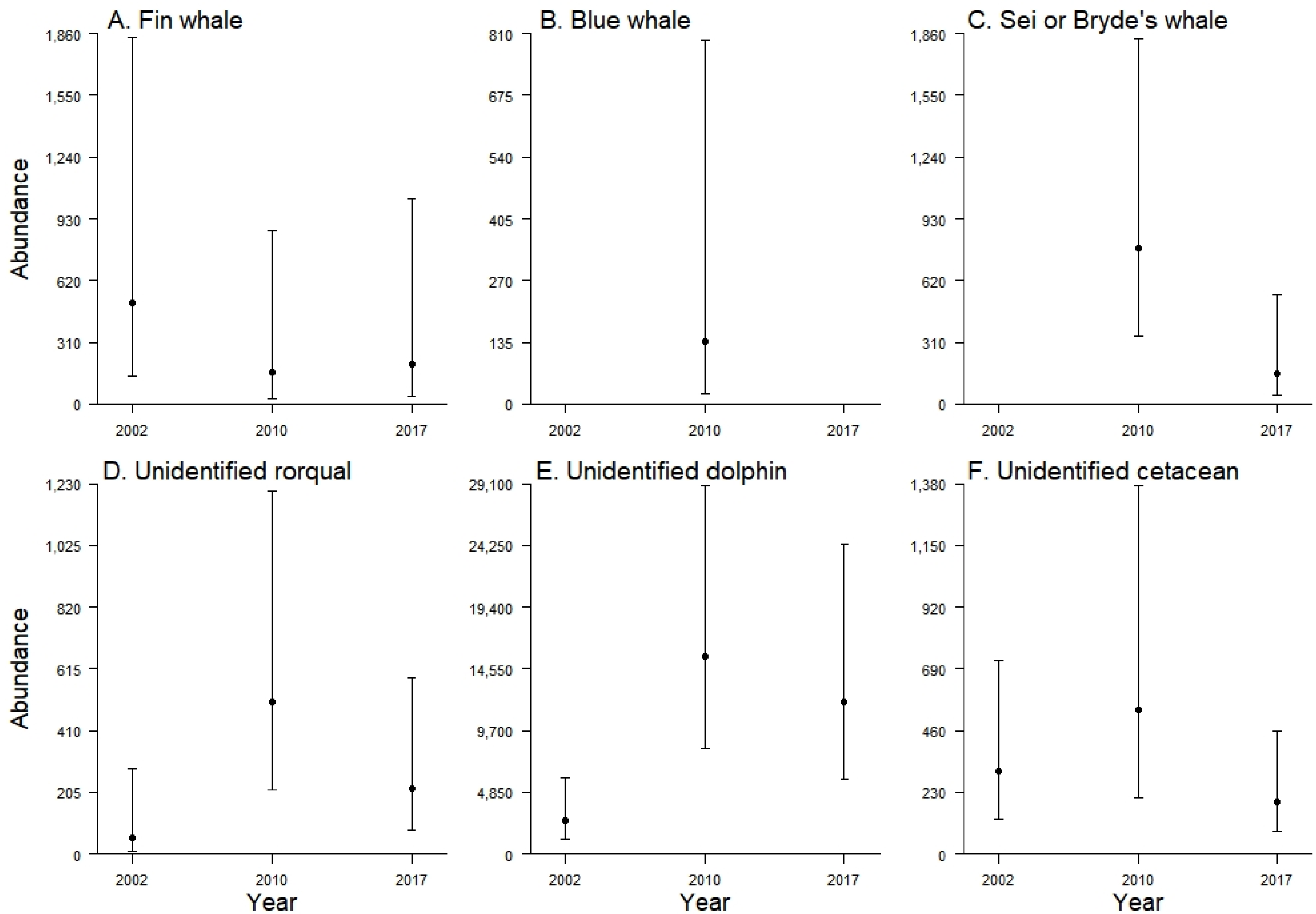

Figure B 13. Estimated abundance (with 95% confidence intervals) of (A) fin, (B) blue, (C) and sei or Bryde's whales, and (D) unidentified rorquals, (E) dolphins, and (F) cetaceans during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey in 2002, 2010, and 2017.

Appendix C: Random Variation in the Encounter Rate

The abundance estimates of Bryde's and Cuvier's beaked whales resulting from the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) of 2010 and 2017 had non-overlapping 95% confidence intervals (Table 4; Figure B 11F and Figure B 12E) suggesting a significant difference between the two HICEAS estimates for each species. The differences in the estimates are reflected in the encounter rates of each species between years, with the encounter rate of Bryde's whales based on 19 and 2 systematic-effort sightings from HICEAS 2010 and HICEAS 2017, respectively, and the encounter rate of Cuvier's beaked whales based on 1 and 7 systematic-effort sightings. A simulation study was conducted to evaluate whether the pronounced variation in the encounter rate of the two species could have occurred by chance if the overall abundance of each population within the U.S. Exclusive Economic Zone of the Hawaiian Islands (Hawaiian EEZ) did not change.

Consistent with the bootstrap routine used in the abundance estimation, 150-km segments of systematic survey effort were created for each HICEAS year (2002, 2010, and 2017). These effort segments were linked to their associated number of systematic-effort sightings used in the abundance estimation (N_{EST} in Table 1) and then pooled for use in a bootstrap procedure. Systematic survey effort was stratified between the main Hawaiian Islands (MHI) and the outer EEZ in 2002, with a higher density of effort in the MHI stratum. Therefore, effort segments from each year were generated by stratum to make the bootstrap procedure compatible over all years. Effort segments were sampled with replacement 1,000 time according to the number of segments surveyed in each stratum in each year (i.e., more effort segments were drawn in the MHI stratum in 2002 than in 2010 and 2017; Table C 1). For each bootstrap iteration, the number of sightings of each species were summed over all effort segments in the sample.

The simulated number of sightings of Bryde's and Cuvier's beaked whales in each survey year has a peak between 8–10 and 2–3 sightings, respectively, although the shape of each distribution varies slightly among years (Figure C 1). For Bryde's whales, the simulated number of sightings in 2002 was close to what was observed, with 13.1% of iterations containing 9 sightings (the observed number of sightings in that year) and 37.7% of them containing 8−10 sightings. However, the simulated number of sightings in 2010 and 2017 was substantially lower and higher, respectively, than what was observed, with only 0.7% of iterations containing ≥19 sightings in 2010, and 0.3% of iterations containing ≤2 sightings in 2017. For Cuvier's beaked whales, the simulated number of sightings in 2002 and 2010 were close to what was observed, with 21.6% of iterations for 2002 containing 2 sightings (the observed number of sightings in that year) and 11.5% of them for 2010 containing 1 sighting (the observed number in that year). However, the simulated number of sightings 2017 was markedly lower than what was observed, with only 7.0% of iterations containing ≥7 sightings.

While the simulated probabilities associated with the Bryde's whale encounter rate in 2010 and 2017 and the Cuvier's beaked whale encounter rate in 2017 are relatively low, they indicate the observed encounter rates could have occurred by chance when the abundance of these species was constant. Thus random variation in encounter rate may be playing a pronounced role in the estimates of Bryde's and Cuvier's beaked whale abundance. However, the fact that these probabilities are low, particularly for Bryde's whales, suggests that other factors are also influencing the estimates, including shifts in distribution in and out of the Hawaiian EEZ and true changes in population abundance. In other words, it is possible that the abundance of Bryde's and Cuvier's beaked whales within the Hawaiian EEZ differed significantly between 2010 and 2017.

Table C 1. Number of systematic survey effort segments and total survey distance (km) in each survey stratum in each year of the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS), where stratum is in either the main Hawaiian Islands (MHI) or outer U.S. Hawaiian Islands Exclusive Economic Zone (EEZ).

Year	MHI segments	MHI distance	Outer-EEZ segments	Outer-EEZ distance	Bryde's	Cuvier's beaked
2002	30	3,540	99	13,473	9	2
2010	15	1,739	106	14,405	19	1
2017	14	1,352	111	14,858	2	7

The number of sightings of Bryde's and Cuvier's beaked whales observed during each HICEAS year was compared to the simulated distributions in Figure C 1.

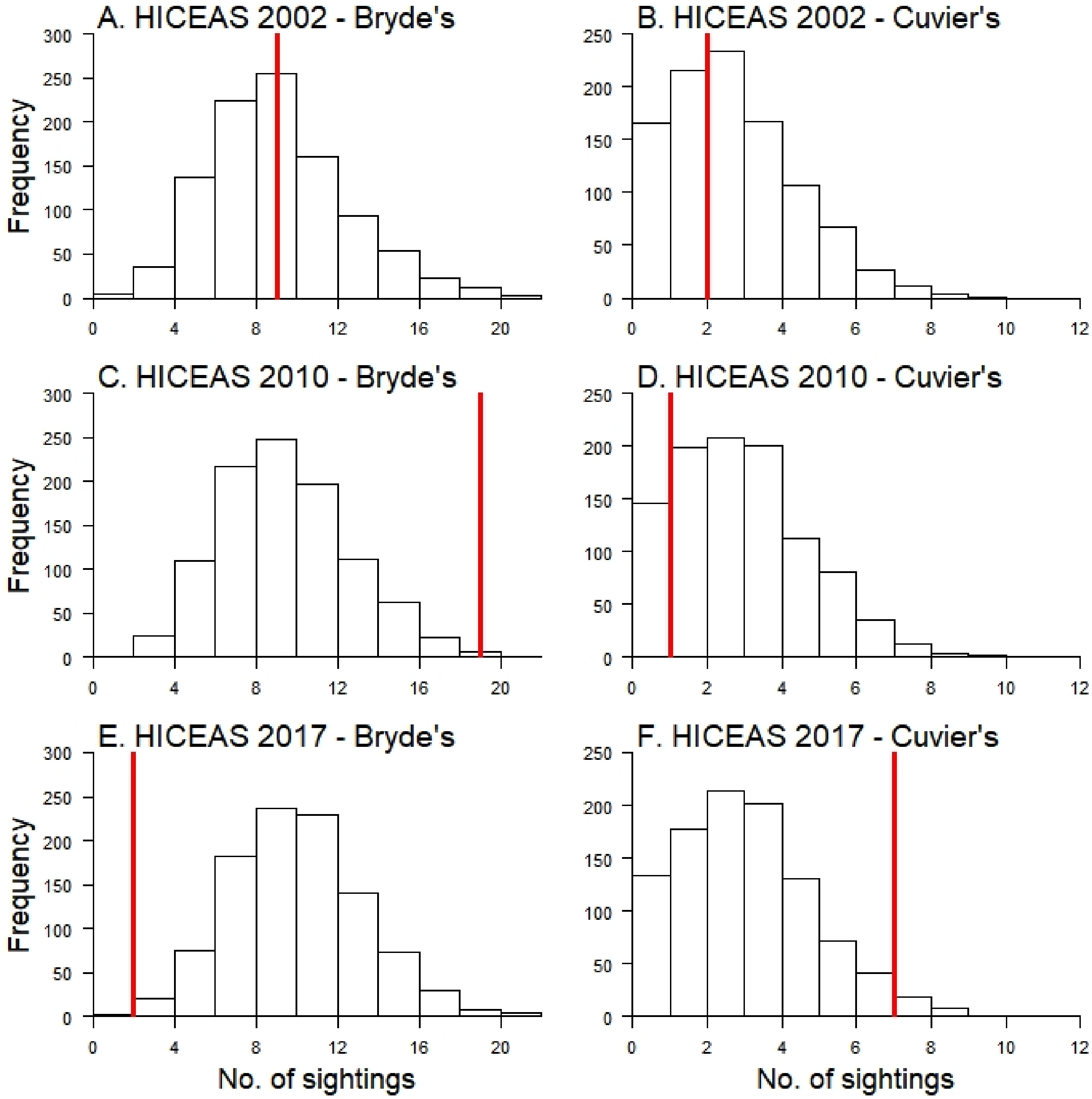

Figure C 1. Distributions of the simulated number of sightings of Bryde's and Cuvier's beaked whales resulting from the bootstrap for each year of the Hawaiian Islands Assessment and Ecosystem Assessment Survey (HICEAS), where (A) and (B) are the distributions of sightings of each species for HICEAS 2002, (C) and (D) are the distributions for HICEAS 2010, and (E) and (F) are the distributions for HICEAS 2017.

The number of sightings of each species actually observed during each HICEAS year is represented by the red line.