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ABSTRACT

Three stocks of false killer whales (*Pseudorca crassidens*) can be differentiated within the U.S. Exclusive Economic Zone of the Hawaiian Islands (Hawaiian EEZ): an insular main Hawaiian Islands stock, a dispersed pelagic stock, and a newly recognized Northwestern Hawaiian Islands stock. Current abundance estimates are needed for the pelagic and Northwestern Hawaiian Islands stocks. To this end, a ship-based line-transect survey of the Hawaiian EEZ was conducted in the summer–fall of 2010, resulting in 6 systematic-effort visual sightings of pelagic (n = 5) and Northwestern Hawaiian Islands (n = 1) false killer whale groups. These sightings were combined with data from multiple sources and analyzed within the conventional line-transect estimation framework, although the detection function, mean cluster size, and encounter rate were estimated separately so as to appropriately incorporate data collected using different methods. Unlike previous line-transect analyses of false killer whales, subgroups were treated as the analytical unit instead of groups because subgroups better conform to the specifications of line-transect theory. Bootstrap values (n = 5000) of the line-transect parameters were randomly combined to estimate the variance of stock-specific abundance estimates. Hawaii pelagic and Northwestern Hawaiian Islands false killer whales were estimated to number 1503 (CV = 0.66) and 552 (CV = 1.09) individuals, respectively. These estimates can be considered positively biased to an unknown extent due to the effect of vessel attraction.

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INTRODUCTION

False killer whales (*Pseudorca crassidens*) are widely distributed in tropical waters. Two stocks of false killer whales have been previously recognized within the U.S. Exclusive Economic Zone of the Hawaiian Islands (Hawaiian EEZ): an insular stock associated with the main Hawaiian Islands and a more broadly distributed pelagic stock (Caretta et al., 2010). The insular main Hawaiian Islands stock was estimated to number 161 (CV = 0.20) individuals from 2006 to 2009 using mark-recapture methods and has experienced a decline of approximately 9% per year (Oleson et al., 2010). This stock has been proposed for listing under the Endangered Species Act (75 FR 70169, 17 November 2010). The abundance of the pelagic stock was estimated to be 484 (CV = 0.93) individuals based on data collected during the first Hawaiian Cetacean Ecosystem Assessment Survey (HICEAS), a line-transect survey of the Hawaiian EEZ in 2002 (Barlow and Rankin, 2007). False killer whales are known to depredate catch in the Hawaii-based pelagic longline fisheries. This depredation results in economic losses to the fisheries and creates the potential for false killer whale mortality or serious injury (Forney et al., 2011). Assessments mandated by the U.S. Marine Mammal Protection Act have shown that the bycatch of pelagic false killer whales in the Hawaiian EEZ exceeds allowable levels (e.g., Caretta et al., 2010). Accordingly, a Take Reduction Team was convened by the National Marine Fisheries Service (NMFS) in 2010 to prepare a Draft Take Reduction Plan for reducing false killer whale bycatch (Forney et al., 2011). Abundance estimates used to inform marine mammal stock assessments are considered outdated after 8 years (NMFS, 2005). Thus, an update to the 2002 estimate of pelagic false killer abundance is needed.

A second HICEAS was conducted in 2010 as a collaborative effort between the NMFS Pacific Islands Fisheries Science Center (PIFSC) and the Southwest Fisheries Science Center (SWFSC). As with the initial HICEAS in 2002, the primary objective of HICEAS 2010 was to carry out line-transect surveys within the Hawaiian EEZ to estimate the abundance of cetaceans, including the pelagic stock of false killer whales. Genetic and satellite tagging data were also collected during HICEAS 2010 and indicated that false killer whales within the insular waters of the Northwestern Hawaiian Islands warrant recognition as a separate stock, distinct from both the pelagic and insular main Hawaiian Islands stocks (Baird et al., In review; Martien et al., 2011). The objective of the present report is to estimate the abundance of false killer whales in the pelagic region of the Hawaiian EEZ and the insular waters of the Northwestern Hawaiian Islands based on the visual line-transect detections from HICEAS 2010. Acoustic line-transect detections obtained during HICEAS 2010 were not included in the present estimation because they are still being processed and analyzed.

METHODS

Data Collection

The second HICEAS was conducted during the summer–fall of 2010 aboard two National Oceanographic and Atmospheric Administration (NOAA) research vessels. Survey dates for the 68-m NOAA Ship *McArthur II* (McII) were 4 August to 10 December 2010, and survey dates for the 68-m NOAA Ship *Oscar Elton Sette* (OES) were 1 September to 29 October 2010. The HICEAS 2010 study area was the U.S. EEZ of the Hawaiian Islands (Fig. 1). The line-transect survey design was similar to that of HICEAS 2002 (Barlow, 2006), with parallel transect lines that were oriented WNW–ESE to minimize the effects of the dominant swells in the region. These transect lines formed a grid that provided comprehensive coverage of the study area. The original 2002 grid was established by randomly placing an initial transect line and then positioning other transect lines parallel at a spacing of approximately 40 km apart. Transect lines in 2010 were placed midway between each of the 2002 lines, allowing for denser coverage of the study area over the two surveys. Unlike HICEAS 2002, HICEAS 2010 survey effort was not stratified to intensively sample the main Hawaiian Islands. Thus, transect density was roughly uniform throughout the study area. Both vessels surveyed at a speed of 10 kts. Transits to and from ports and island circumnavigations were not a part of the systematic survey grid, although the visual observers generally remained on-effort, following standard observation protocols. Sightings made during this nonsystematic effort and while off-effort were not suitable for the estimation of false killer whale encounter rates in the study area, but were used to inform other line-transect parameters, as appropriate.

The general visual observation methods employed during HICEAS 2010 are well established, having been in use by the SWFSC for the last 3 decades (e.g., Barlow and Forney, 2007), including surveys in the Pacific Islands region (Barlow, 2006; Barlow and Rankin, 2007). Observation teams comprised 6 observers who rotated through 3 viewing positions and searched for cetaceans using 25× binoculars and unaided eyes from the approximately 15-m flying bridge. If cetaceans were sighted within 5.6 km of the trackline by an on-effort observer, the ship diverted from the trackline toward the sighting so that species, proportion of species present (for mixed-species groups), and an estimate of group size could be determined. A protocol specific to sightings of false killer whales (hereafter referred to as the group-size estimation protocol) was established for HICEAS 2010 to obtain more accurate estimates of group size (see below). Along with basic environmental data (e.g., Beaufort sea state, swell height, and visibility), data recorded for each sighting included the time, location, species, initial bearing and radial distance to the sighting (used to compute the perpendicular distance from the trackline), identity of observers and their independent estimates of group size ("best," "high," and "low"), and proportion of each species present. If weather, animal behavior, and research priorities permitted, a small boat was launched following species identification and enumeration to collect photo-identification images and biopsy samples for the purposes of individual and stock identification.

Group-size Estimation Protocol

When organisms occur in aggregations (or clusters) of individuals, the cluster size of a sighting becomes an integral component of line-transect abundance estimation and should be accurately measured (Buckland et al., 2001). Cluster size in cetaceans has traditionally been interpreted as biological group size (Barlow et al., 2001), but visual observation may underestimate group size if group members are spatially diffuse or prolonged divers (Barlow and Taylor, 2005). False killer whale groups can consist of multiple dispersed subgroups, and total group size may be underestimated if encounter duration is insufficient (Baird et al., 2008). During line-transect surveys of the U.S. EEZ around Palmyra Atoll, Barlow and Rankin (2007) found that some false killer whale subgroups detected acoustically were missed by the visual observers. The group-size estimation protocol implemented during HICEAS 2010 combined visual and acoustic information to find and enumerate the sizes of subgroups, allowing for a more accurate estimation of total group size. Specifically, when false killer whales were visually detected, acoustic information was used to direct the ship to the perceived center of the group. Additional turns were made to localize and approach subgroups detected by either observation method. The on-effort visual observers, supplemented by off-effort observers, were responsible for enumerating the sizes of subgroups, with one observer assigned to each detected subgroup to ensure complete coverage. Passage through the group continued until no further subgroups were acoustically or visually detected ahead of the beam of the ship.

In practice, the group-size estimation protocol was difficult to implement due to logistical constraints, technical difficulties, and whale behavior. Therefore, it was not successfully executed for all false killer whale sightings during HICEAS 2010. Additionally, accounting for false killer whale groups in their entirety resulted in unanticipated challenges when attempting to apply the rules for clustered objects dictated by line-transect theory. Specifically, a detected group (i.e., cluster) should only be considered a sighting for analysis if the center of the group is within the analytical truncation distance (Buckland et al., 2001). As reported below, false killer whale subgroups can span tens of kilometers. Thus, groups can exceed the transect strip width, as well as the visual sighting horizon, creating a spatial scale mismatch between the observed group and the theoretical framework of line-transect analysis. Incorporating all subgroups into an estimate of group size would overestimate density in the study area due to the inclusion of individuals outside the truncation distance. Subjecting false killer whale detections to the group center criteria is impractical because: 1) the center of a large, dispersed, and mobile group can be difficult to identify; 2) the group center does not have the relevance to the detection process intended by Buckland et al. (2001), and 3) the criteria could lead to the loss of sightings of this rarely encountered species. These post-hoc considerations led to the determination that false killer whale subgroups, not groups, more appropriately represent a detectable unit and better conform to the line-transect definition of a cluster (Buckland et al., 2001). As such, subgroups served as the analytical unit in the present abundance estimation.

Abundance Estimation

Multiple-covariate line-transect methods are increasingly being used to estimate the density and abundance of cetaceans (e.g., Barlow and Forney, 2007) and were previously applied to the Hawaii pelagic stock of false killer whales (Barlow, 2006; Barlow and Rankin, 2007). The multiple-covariate framework accounts for heterogeneity from covariates other than perpendicular distance in the detection function (Marques and Buckland, 2004), which can be modeled using sightings pooled from multiple surveys, although the remaining components of the associated estimator are necessarily linked to sightings from the current study (e.g., Barlow, 2006). The ability to model detection probabilities from an enlarged pool of sightings is advantageous for study regions such as the Hawaiian EEZ, where cetacean sighting rates are comparatively low (Barlow, 2006). However, the estimation of the other components solely by a restricted set of sightings limits the uncertainty that can be represented by those parameters, particularly when sightings are few in number. Further, a preliminary evaluation of the multiple-covariate approach found that it would not sufficiently accommodate the variation in data collection protocols introduced during HICEAS 2010. Therefore, to estimate the density of false killer whales in the pelagic region of the Hawaiian EEZ and the insular waters of the Northwestern Hawaiian Islands, the conventional form of the line-transect estimator was employed:

$$D_i = \frac{n_i \cdot E(s) \cdot f(0)}{2 \cdot L_i \cdot g(0)} \tag{1}$$

where D_i is the density of stock i, n_i is the number of systematic-effort subgroup detections of stock i, $E(s)$ is the expected size of false killer whale subgroups, $f(0)$ is the probability density function of the perpendicular detection distances evaluated at zero distance, L_i is the length of systematic transect lines accomplished in the portion of the study area associated with each stock i, and g(0) is the probability of detection on the trackline. Data from other sources were incorporated into the parameter estimation because of the limited number of HICEAS 2010 sightings. The implementation of the group-size estimation protocol during HICEAS 2010 prevented estimating each of the line-transect parameters with the full data set. Thus, the parameters were estimated separately, as described below, using an appropriate data subset that met parameter-specific assumptions. Variances for all parameters were obtained using bootstrap methods.

Detection Function

To achieve a more robust sample size for modeling the detection function of subgroups, sightings of false killer whales from HICEAS 2010 were pooled with a subset of false killer whale sightings made during SWFSC and PIFSC line-transect surveys of the eastern tropical and central North Pacific between 1986 and 2009. This combined data set included a small number of sightings that were collected during nonsystematic survey effort. For all of the sightings, the initial detection was assumed to represent a single subgroup that may or may not have been a part of a larger group. Thus, despite the different approaches used to estimate total group size once a sighting was detected, the HICEAS 2010 and earlier sightings were regarded as comparable in terms of the detection process.

Potential heterogeneity introduced by pooling sightings from different surveys was minimized by restricting the sample to sightings collected under conditions similar to those encountered during HICEAS 2010. Because there were no mixed-species sightings of false killer whales during HICEAS 2010, multispecies sightings from previous years were excluded from pooling to eliminate the influence of other species on the detection process. An exploratory multiple-covariate analysis was conducted to identify additional sources of heterogeneity. Specifically, a half-normal model was used to evaluate the detection probabilities of available sightings as a function of perpendicular distance from the trackline and relevant covariates (Barlow et al., 2001). Only half-normal models were employed in modeling the detection function because they exhibit greater stability than other models when fitting cetacean sighting data (Gerrodette and Forcada, 2005). Geographical region (eastern tropical or central North Pacific) and Beaufort sea state (restricted to values between 0 and 6) were identified as important determinants of detection probability. These two covariates are likely linked because calm conditions (Beaufort states 0–2) are not commonly encountered within the central North Pacific. Thus, to make the pooled sample reflect the higher sea state conditions characteristic of the central North Pacific, only sightings made in Beaufort states 3-6 were included. A two-sample Kolmogorov-Smirnov test was performed on the pooled sightings to evaluate the similarity in the distribution of Beaufort states by region. A lack of significant difference between these distributions was used to indicate that the detected heterogeneity had been minimized.

A half-normal model (with no adjustments) was fitted to the perpendicular distances of the combined data set, which was truncated at 4.5 km to improve model fit (Buckland *et al.,* 2001; Barlow, 2006; Barlow and Rankin, 2007). Program Distance (Thomas et al., 2010) was used to estimate $f(0)$ and its inverse, the effective strip width (*ESW*; the distance from the trackline for which as many individuals were detected beyond as were missed within) and to obtain a bootstrap estimate (n = 5000 iterations) of the coefficient of variation (CV).

Expected Subgroup Size

Subgroup structure was not explicitly detailed or quantified in false killer whale sightings from earlier line-transect surveys. Thus, there are few existing observations of subgroup size. The only available values are those resulting from the group-size estimation protocol during HICEAS 2010, as well as a few observations made using a new subgroup-oriented passing mode protocol introduced during a 2011 survey of the U.S. EEZ around Palmyra Atoll (PIFSC, unpublished data). These observations of subgroup size were averaged to estimate $E(s)$. When more than one observer provided a "best" estimate of size for a given subgroup, the geometric mean of the estimates was used. In some cases, observers recorded a "high" and "low" value of subgroup size, but were unable to provide a "best" estimate. For these subgroups, an average "best":"low" ratio, computed from subgroups with the full complement of estimates, was used to determine a "best" estimate of subgroup size. The pooled values of subgroup size were randomly sampled with replacement 5000 times to estimate the CV of $E(s)$.

Encounter Rate

Encounter rates in cetacean surveys are typically based on the number of sightings per unit of effort distance (e.g., Barlow, 2006). In the present analysis, the encounter rate of each stock (n_i/L_i) represents the number of subgroup detections divided by the length of transect lines surveyed. Counting sightings for which the group-size estimation protocol was attempted as a single detection would underestimate n_i/L_i (and thus density) because these sightings contained multiple subgroups. However, because the group-size estimation protocol directed the ship away from the trackline and toward subgroups, it is unknown how many of the subgroups would have been visually detected had the ship remained on the trackline. Therefore, the expected number of detected subgroups for these sightings was determined probabilistically.

Estimating the expected number of detected subgroups for the group-size estimation protocol sightings first involved projecting an on-effort trackline representing the path the ship would have taken past the group if it had remained in passing mode on the initial detection. This projected on-effort trackline continued until all identified subgroups would have passed the beam of the ship. The initial location of each subgroup was determined from the recorded bearing and distance of the subgroup from the actual path of the ship. Perpendicular distances from these locations to the projected on-effort trackline were then calculated. Subgroups more than 4.5 km from the projected trackline were not considered further, as they were beyond the analytical truncation distance. Of the subgroups within 4.5 km of the projected trackline, the subgroup closest to the location of the initial visual detection was considered to represent the initial visual detection and assigned a detection probability of 100%. Detection probabilities for the remaining subgroups were based on the distance of the subgroup from the projected trackline and the estimated detection function. These probabilities were summed to compute the expected number of subgroups that would have been detected if the vessel had remained in passing mode.

In cases when the group-size estimation protocol was unsuccessfully executed for a sighting (i.e., the number, sizes, and locations of subgroups could not be determined), the number of subgroups and their average detection probabilities were estimated from other available data. The total group size of the sighting was divided by the point estimate of $E(s)$ to estimate the number of subgroups present. The average proportion of subgroups within 4.5 km of the projected trackline for the successful group-size estimation protocol sightings was employed to determine how many subgroups were within the 4.5 km truncation distance. The first of these subgroups was assigned a detection probability of 100%, while the others were assigned the average detection probability estimated for the study (i.e., ESW divided by the truncation distance). The effort distance associated with all attempted group-size estimation protocol sightings was adjusted to include the length of the projected on-effort trackline.

The expected number of detected subgroups for each sighting was summed over all stock-specific sightings to produce n_i. The variance of n_i/L_i was estimated using a bootstrap procedure. Specifically, the systematic survey coverage of the range of each stock was divided into 150 km effort segments, which approximates the distance surveyed in a single day (Barlow, 2006). These effort segments and their associated sightings were randomly sampled 5000 times. When a segment was drawn that contained an attempted group-size estimation protocol sighting, the number of detected subgroups was stochastically determined within the bootstrap based on the estimated detection probabilities described above. For unsuccessful group-size estimation protocol sightings, uncertainty in the number of subgroups present was included in the bootstrap by drawing a random sample of subgroups from the available observations used to estimate $E(s)$ until the sum of all subgroups in a draw totaled the estimate of total group size recorded for the sighting.

Density and Abundance

Based on the range of subgroup sizes observed in the present study, the $g(0)$ estimate (0.76, CV = 0.14) for small groups (< 20 individuals) of delphinids (Barlow, 1995) was employed in the analysis. Bootstrap values (n =5000) were obtained following the method of Barlow (2006), by modeling $g(0)$ as a logit-transformed deviate with a mean and variance chosen to give the estimated $g(0)$ and CV. For each stock, density (individuals per km^2) was calculated using Equation (1) and the point estimate of each parameter. Variance in density was estimated by randomly combining the 5000 bootstrap values of $f(0)$, $E(s)$, n_i/L_i, and $g(0)$. Abundance was determined by multiplying the density values by the portion of the study area associated with each false killer whale stock (Fig. 1). For pelagic false killer whales, this area is 2,381,486 km^2, which encompasses the Hawaiian EEZ minus the land masses of the main and Northwestern Hawaiian Islands, as well as waters within 40 km of the main Hawaiian Islands, which are considered to be occupied exclusively by the insular main Hawaiian Islands stock of false killer whales (Oleson et al., 2010). The full range of the recently documented Northwestern Hawaiian Islands stock of false killer whales is unknown, but a boundary combining the Papahānaumokuākea Marine National Monument with insular waters of the westernmost main Hawaiian Islands (Kauaʻi and Niʻihau) is most consistent with available photo-identification and satellite tagging data (Baird et al., in review). The area incorporated is 414,743 km^2, which includes the Monument with its eastern edge extended to a 93 km buffer east of Kauaʻi minus the land mass of the Northwestern Hawaiian Islands, Kauaʻi, and Niʻihau.

RESULTS

Survey Sightings

On-effort visual searches for pelagic false killer whales in the Hawaiian EEZ encompassed 16,145 km of systematic transects in Beaufort sea states from 0 to 6 (Fig. 1), with most (94.5%) of the effort conducted in Beaufort states 3-6. Five systematic-effort sightings of pelagic stock false killer whales were made during HICEAS 2010 (Table 1). The group-size estimation protocol was successfully implemented for one systematic-effort pelagic sighting (McII 241), which included 16 localized subgroups that spanned over 35 km and were tracked for more than 2 hours (Fig. 2A). The group-size estimation protocol was attempted for another systematic-effort pelagic sighting (McII 35), but the execution was unsuccessful and the observed subgroups were not quantified or localized (Fig. 2B). The three remaining systematic-effort sightings consisted of single, small subgroups (Table 1). The acoustic observers were off-effort during these sightings, precluding the use of the group-size estimation protocol, but no additional subgroups were visually detected.

On-effort visual searches for false killer whales within the assumed stock range of the Northwestern Hawaiian Islands stock covered 2901 km of systematic transects in Beaufort sea states from 0 to 6 (Fig. 1). Only one systematic-effort sighting was made of false killer whales from the Northwestern Hawaiian Islands stock (Table 1). The group-size estimation protocol was successfully implemented for this sighting (OES 86), which included 18 subgroups that spanned over 25 km and were also tracked for more than 2 hours (Fig. 2C). Eight additional nonsystematic-effort (n = 4) and off-effort (n = 4) sightings of false killer whales were made during HICEAS 2010, including 3 sightings from the pelagic stock, 4 from the Northwestern Hawaiian Islands stock, and 1 from the main Hawaiian Islands insular stock (Table 1). These sightings were not part of the systematic visual line-transect survey and were therefore excluded from the encounter rate estimation. However, 3 sightings (McII 140, 142, and 224) collected during nonsystematic effort were suitable for inclusion in the pooled sample that was used to estimate the detection function, and 1 off-effort sighting (McII 61) conducted using the group-size estimation protocol provided estimates of subgroup size (Table 1).

Estimator Components

A total of 62 systematic-effort (n = 57) and nonsystematic-effort (n = 5) false killer whale sightings made from 1986 to 2010 in the eastern tropical Pacific (n = 39 sightings, all systematic-effort) and central North Pacific (n = 23 sightings, includes the 6 systematic-effort and 3 applicable nonsystematic-effort HICEAS 2010 sightings) met the pooling criteria for modeling subgroup detection probabilities (Table 2). The 2-sample Kolmogorov-Smirnov test did not detect a difference in the distribution of Beaufort sea states by region (D = 0.13, p-value = 0.97), indicating that the heterogeneity associated with Beaufort state and region had been minimized. The pooled sample includes sightings that occurred disproportionately more often in the distance bin closest to the trackline (Fig. 3). The resulting detection function (Fig. 3) and bootstrap resampling led to an $f(0)$ estimate of 0.43 (CV = 0.11) km^{-1} (ESW = 2.31).

Forty-four values of observed false killer whale subgroup size were available for the estimation of $E(s)$ (Fig. 4). These observations resulted from the group-size estimation protocol implemented during systematic-effort sightings McII 241 (n = 16 subgroups) and OES 86 (n = 18 subgroups) and off-effort sighting McII 61 (n = 6 subgroups). An average "best":"low" size ratio (1.2; calculated from 22 subgroups) was used to establish subgroup size for 11 of the McII 241 subgroups for which "best" estimates were not provided. The aforementioned 2011 Palmyra EEZ survey and new passing mode protocol contributed four values of subgroup size, ranging from 1 to 7 individuals (PIFSC, unpublished data). Bootstrap resampling of the assembled observations produced an $E(s)$ of 3.11 (CV = 0.12) individuals.

The group-size estimation protocol was successfully implemented for one systematic-effort sighting in each stock, which required probabilistic determination of the expected number of detected subgroups. For the pelagic sighting McII 241, 10 of the 16 (62.5%) subgroups were within 4.5 km of the projected trackline (Fig. 2A), while 7 of the 18 (38.9%) subgroups in the Northwestern Hawaiian Islands sighting OES 86 were within 4.5 km of the projected trackline (Fig. 2C). Thus, 9 of the McII 241 subgroups and 6 of the OES 86 subgroups were subject to probabilistic selection according to the estimated probability of detection, which was computed using the point estimate of the half-normal scale parameter ($\sigma = 1.88$). The expected number of detected subgroups for sightings McII 241 and OES 86 is 6.2 and 4.4, respectively. The expected number of detected subgroups was also probabilistically determined for pelagic systematic-effort sighting McII 35, in which the group-size estimation protocol was unsuccessfully executed (Fig. 2B). Based on the total group size of this sighting (22.6; Table 1) and the estimate of $E(s)$, the expected number of subgroups present in McII 35 is 7.3. Applying the average proportion of subgroups within 4.5 km of the projected trackline for sightings McII 241 and OES 86 (0.51), the expected number of McII 35 subgroups within 4.5 km is 3.7. Factoring in a 100% detection probability for the first subgroup and the average detection probability (0.51) for the remaining subgroups, the expected number of detected subgroups for McII 35 is 2.4. Given the expected number of detected subgroups for sightings McII 241 and McII 35 and the 3 other pelagic systematic-effort sightings of single subgroups, $n_{pelagic}$ is 11.6 subgroups. Because OES 86 was the only systematic-effort sighting of the Northwestern Hawaiian Islands stock, n_{NWHI} is 4.4 subgroups. The division of on-effort survey coverage into 150-km effort segments for the bootstrap procedure resulted in 114 effort segments in the Hawaiian EEZ stratum and 26 in the Northwestern Hawaiian Islands stratum. The bootstrap estimates of n_i/L_i for the pelagic and Northwestern Hawaiian Islands stocks are 0.07 (CV = 0.60) subgroups 100 km^{-1} and 0.15 (CV = 1.04) subgroups 100 km^{-1}, respectively.

Abundance Estimates

The 2010 abundance of pelagic stock false killer whales was estimated to be 1503 (CV = 0.66) individuals. The 2010 abundance of Northwestern Hawaiian Islands stock false killer whales was estimated to be 552 (CV = 1.09) individuals. A summary of the stock-specific estimates of the line-transect parameters, density, and abundance is shown in Table 3.

DISCUSSION

The number of systematic-effort false killer whale sightings ($n = 6$) made during HICEAS 2010 was much higher than the total ($n = 1$) resulting from HICEAS 2002 (Barlow 2006). Total systematic-effort survey coverage was marginally higher during HICEAS 2010 (19,046 km) as compared to HICEAS 2002 (17,050 km). However, approximately 3550 km of the HICEAS 2002 effort was devoted to an intensive survey of the main Hawaiian Islands. Thus, survey coverage within the broader Hawaiian EEZ was greater in 2010. The increased number of sightings during HICEAS 2010 could be linked to this expanded coverage, but could also be explained by more suitable sighting conditions in the study area in 2010. Additionally, oceanographic differences between the two survey periods may have led to changes in the distribution or abundance of false killer whales in the Hawaiian EEZ. These hypotheses have not yet been examined, but could account for the relatively higher sighting rates of most species during HICEAS 2010. Alternatively, the larger number of 2010 sightings may represent random variation in the sampling process or in the distribution of false killer whales. There were also a greater number of combined non-systematic and off-effort sightings during HICEAS 2010 (n = 8), as compared to HICEAS 2002 (n = 1), because of additional research activities directed at false killer whales in 2010 (i.e., nonsystematic surveys around the Northwestern Hawaiian Islands and the relocation of satellite-tagged individuals; Baird et al., in review).

The line-transect abundance estimation approach employed in the present analysis departed from that previously used for Hawaii pelagic false killer whales (Barlow, 2006; Barlow and Rankin, 2007) and other cetaceans (e.g., Barlow and Forney, 2007). The multiple-covariate framework, which addresses heterogeneity in the detection function and thus accommodates the pooling of sightings from multiple surveys, was not used because that approach links the estimation of the other line-transect parameters to the sightings of the current study. In the present analysis, this linkage would have limited the ability to adequately represent uncertainty in those parameters and would not have allowed for adjustments to address bias introduced by unavoidable variation in data collection protocols. Using the conventional form of the line-transect estimator and separately estimating each of the parameters offered a workable way to appropriately incorporate data obtained from various sources and collected with different methods and thus produce the most robust and unbiased abundance estimate possible.

The group-size estimation protocol introduced during HICEAS 2010 represented a significant change in data collection methodology for false killer whales, which had to be accommodated in the abundance estimation. This protocol was established because previous studies had demonstrated that visual observers were not detecting all false killer whale subgroups in a group, with the result that overall group sizes were likely being underestimated (Barlow and Rankin, 2007). As biological group size has generally served as the unit of detection and analysis in cetacean studies (Barlow et al., 2001), an emphasis on obtaining more accurate estimates of total false killer whale group size appeared warranted. In hindsight, while the group-size estimation protocol provided an effective way to assess the size and spatial spread of false killer whale groups, it produced data that were difficult to analyze using standard line-transect methods. However, the protocol sightings did reveal the degree to which false killer whale groups do not adhere to the definition of cluster associated with line-transect methodology (Buckland et al., 2001) and therefore should not serve as the analytical unit. In contrast, subgroups are more aligned with the cluster concept and represent what is first detected by a visual observer, not the group as a whole, which may extend far beyond viewing range. Thus, subgroups are a more appropriate analytical unit, an adjustment that was applied post-hoc in the present estimation, but should be more fully integrated into future data-collection protocols. In that regard, a revised protocol for false killer whales was instituted during a 2011 survey of the Palmyra EEZ, whereby the ship remained in passing mode until the visual observers had an opportunity to detect all subgroups within a group (PIFSC, unpublished data). While this protocol will generate data more suitable for line-transect abundance estimation, properly accounting for the dependence between subgroup sightings warrants additional consideration.

As in the multiple-covariate approach, previous sightings were pooled with those from HICEAS 2010 to model the detection function of false killer whale subgroups. However, because the multiple-covariate approach was not used, heterogeneity from factors other than perpendicular distance had to be minimized in the pooled sample. To reduce the impact of other species on the detection process, sightings of other large delphinids and mixed-species false killer whale sightings were excluded from the pooled sample, in contrast to detection function models previously applied to false killer whales (Barlow, 2006; Barlow and Rankin, 2007). Exploratory analyses determined that other sources of discernible heterogeneity were the effects of geographical region (eastern tropical or central North Pacific) and Beaufort sea state, which are likely linked because of the rougher seas within the central North Pacific. When the sighting pool was refined to include only the higher sea state conditions (i.e., Beaufort states 3–6) more frequently encountered in the central North Pacific, this heterogeneity was no longer detected statistically. It is possible that heterogeneity from other factors remained in the pooled sample, but was not detectable with the available sample size. The point estimate of ESW (2.31) presented here does not differ appreciably from that previously attributed to Hawaii pelagic false killer whales (2.24; Barlow and Rankin, 2007) and other large delphinids (Barlow, 2006; Barlow and Forney, 2007).

The histogram of subgroup detections by perpendicular distance indicated that they were seen disproportionately more often close to the trackline (Fig. 3), which is not ideal for modeling the detection function (Buckland et al., 2001) and is suggestive of false killer whale movement toward the ship prior to detection by the visual observers. One of the primary assumptions of line-transect sampling is that objects are detected prior to a response toward or away from the observer (Buckland et al., 2001). Attractive movement leads to a reduced estimate of ESW and thus results in a density estimate that is positively biased. Vessel attraction has been documented for other cetacean species (e.g., Turnock and Quinn, 1991; Palka and Hammond, 2001) and there are anecdotal records of such behavior for false killer whales, both during research surveys (SWFSC and PIFSC, unpublished data) and by longline fishermen (TEC, 2009). During a survey of the main Hawaiian Islands in 2009, false killer whales were seen approaching the stern wake of the ship before the visual observers detected another portion of the group forward of the vessel (PIFSC, unpublished data). Likewise, for 64.3% ($n = 9$) of the HICEAS 2010 false killer whale sightings, the visual observers noted on the sighting forms that animals were moving toward the ship. Additionally, acoustic observers during several surveys have recorded false killer whales in close proximity to the towed hydrophone array, both before and after detection by the visual observers (SWFSC and PIFSC, unpublished data). Targeted analysis of available acoustic data may yield significant insights into the magnitude of vessel attraction by false killer whales at various distances from the trackline and allow for the estimation of correction factors aimed at reducing the positive bias in density estimates. At present, the use of the half-normal model to estimate the detection function minimized the impact of vessel attraction (Fig. 3) but could not entirely eliminate a positive bias of unknown magnitude in the abundance estimates.

The estimate of $E(s)$ indicates that false killer whale subgroups are generally small, although there is variation (Fig. 4) that will likely be better characterized as more observations of subgroup size become available during future surveys. As this sample size increases, it will also be possible to examine the potential effect of subgroup size on the detection process. The recently revised false killer whale protocol will facilitate the detection of subgroups in a more analytically appropriate manner, although it might introduce greater uncertainty in estimates of subgroup size, as the ship is required to remain in passing mode and not divert from the trackline for subgroup size assessment. However, the revised protocol represents a logistically feasible tradeoff to obtain estimates of subgroup size and encounter rate that are consistent with line-transect assumptions.

For the present estimation of subgroup encounter rate, an approach was developed that incorporated the subgroups associated with sightings for which the group-size estimation protocol was attempted (Fig. 2). Although it is unknown how many subgroups would have been visually detected had the ship remained on the trackline, counting each of these sightings as a single detection would have led to the underestimation of encounter rate. The approach employed probabilistic sampling of subgroups according to their distance from the projected trackline and the estimated detection function. However, these subgroups were localized as the ship was moving toward them, such that their detection location may not represent their original position with respect to the projected trackline. This possibility introduces a potential source of bias of unknown magnitude and direction into the estimation process. The probabilistic sampling approach was expanded to deal with sighting McII 35, for which the group-size estimation protocol could not be successfully completed (Fig. 2B). Neglecting to factor in the known presence of multiple subgroups for this sighting would have underestimated the encounter rate (0.06 subgroups 100 km^{-1} instead of the present estimate of 0.07 subgroups 100 km^{-1}) and led to an underestimate of abundance. For this reason, information from other sightings and parameters was used to estimate the expected number of detected subgroups for this sighting, reducing potential downward bias in the estimation, but introducing additional uncertainty.

The estimated line-transect parameters resulted in density estimates of 0.06 (CV = 0.66) individuals 100 km^{-2} in the pelagic region of the Hawaiian EEZ and 0.13 (CV = 1.09) individuals 100 km^{-2} in the Northwestern Hawaiian Islands (Table 3). Although the point estimate of the 2010 density of pelagic false killer whales is greater than that estimated for the stock in 2002 (0.02 individuals 100 km^{-2}, CV = 0.93; Barlow and Rankin, 2007), the log-normal confidence intervals of these two estimates overlap, indicating that the difference in density is not statistically significant. Little is known about how false killer whales use the pelagic environment of the Hawaiian EEZ, making it difficult to evaluate any potential temporal changes in density. Characterizing the oceanographic environment associated with false killer whale detections would be informative in this regard and could be used to parameterize habitat-based density models (e.g., Becker et al., 2012). The 2010 density of false killer whales in the insular waters of the Northwestern Hawaiian Islands was estimated to be two times that of false killer whales in the pelagic region of the Hawaiian EEZ. An explanation for the higher density in the Northwestern Hawaiian Islands is unavailable. However, the density estimate for this stock is very imprecise and may be positively biased due to the effect of insular-type false killer whale social structure. Most insular false killer whales in the main Hawaiian Islands have been determined to belong to a single social network (Baird et al., 2008). The coarse-scale spatial coverage of the Northwestern Hawaiian Islands during HICEAS 2010 compounded by this social structure could result in overestimates of density if the stock tends to occur as a few large, closely-associated groups. Mark-recapture techniques may prove a more suitable means by which to estimate the abundance of the Northwestern Hawaiian Islands stock of false killer whales, as is the case for insular false killer whales in the main Hawaiian Islands (Oleson et al., 2010).

The abundances of the Hawaii pelagic and Northwestern Hawaiian Islands false killer whale stocks were estimated to be 1503 (CV = 0.66) and 552 (CV = 1.09) individuals, respectively. The greater density of pelagic false killer whales in 2010 translated into a higher abundance estimate than the 484 (CV = 0.93) individuals determined to be in the study area in 2002 (Barlow and Rankin, 2007). While the abundance estimate for false killer whales in the Northwestern Hawaiian Islands is the best available, it is a function of the area used for the stock range, which is presently uncertain, particularly in its western extent (Fig. 1). A better elucidation of this range through telemetry and photo-identification studies is recommended and would likely result in adjustments to the abundance estimate. As aforementioned, both estimates are presumably positively biased as a result of false killer whale vessel attraction, although the extent of the bias is unknown. Until this phenomenon can be better quantified by acoustic analysis or potentially independent observer studies (e.g., Borchers et al., 1998), relevant correction factors are unavailable.

The highly variable nature of false killer whale behavior and group structure creates the potential for a number of biases and uncertainties in line-transect abundance estimation. This effect is compounded by the inevitable logistical and technical difficulties that arise when operating in remote areas at sea. The present analysis attempted to address these characteristics, minimize bias, and quantify uncertainty as appropriately as possible. The incorporation of the acoustic data, when fully processed, may shed light on unresolved issues and facilitate the development of correction factors, as well as independent estimates of abundance.

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Table 1.--Details of HICEAS 2010 false killer whale sightings made during systematic (S) and nonsystematic (N) survey effort and while off-effort (O). Sightings were used, as appropriate, to inform estimation of the line-transect parameters, where $f(0)$ relates to the detection function, $E(s)$ is the mean cluster size, and n_i/L_i is the stock-specific encounter rate. Sightings were assigned to one of three stocks: the pelagic, Northwestern Hawaiian Islands (NWHI), or insular main Hawaiian Islands (MHI) based on genetics (G), location (L), photo-identification (P), proximity (X), or tagging (T).

Date	Ship	Sighting	Effort type	Informed parameter	Group size[1]	Stock	Assignment basis
09/01/10	McII	35	S	$f(0)$, n_i/L_i	22.6	Pelagic	G, P
09/05/10	McII	47	O		10.3	Pelagic	P, L
09/07/10	McII	61	O	$E(s)$	29.9	Pelagic	P, L
09/10/10	McII	74	O		18.3	Pelagic	G, P
09/26/10	OES	86	S	$f(0)$, $E(s)$, n_i/L_i	52.0	NWHI	G, P
09/27/10	McII	98	S	$f(0)$, n_i/L_i	1.9	Pelagic	G, P
09/28/10	McII	103	S	$f(0)$, n_i/L_i	1.0	Pelagic	G, P
10/07/10	McII	140	N	$f(0)$	12.1	NWHI	G, P
10/07/10	McII	142	N	$f(0)$	1.7	NWHI	X
10/20/10	McII	200	O		8.8	NWHI	G, T, P
10/21/10	McII	206	N		20.4	NWHI	G, T, P
10/29/10	McII	224	N	$f(0)$	1.0	MHI	L
10/31/10	McII	231	S	$f(0)$, n_i/L_i	1.0	Pelagic	L
11/10/10	McII	241	S	$f(0)$, $E(s)$, n_i/L_i	41.0	Pelagic	G, P

[1] Either the geometric mean of the best estimates of the observers or the sum of the best estimates of subgroup size.

Table 2.--Distribution of false killer whale sightings made in the eastern tropical Pacific (ETP) and central North Pacific (CNP) from 1986 to 2010 according to Beaufort sea state. Perpendicular trackline distances associated with these sightings were used to model the detection function of false killer whale subgroups.

Beaufort	ETP	CNP
3	12	9
4	17	6
5	10	5
6	0	3

Table 3.--Estimates of line-transect parameters, density (individuals 100 km^{-2}), and abundance for false killer whales in the pelagic region of the Hawaiian EEZ and the insular waters of the Northwestern Hawaiian Islands (NWHI) in 2010. *f*(0) = the probability density function of the perpendicular detection distances evaluated at zero distance; *ESW* = the inverse of *f*(0) and the distance (in km) from the trackline for which as many individuals were detected beyond as were missed within; *E*(*s*) = the expected size of false killer whale subgroups; *n*/*L* = the subgroup encounter rate (presented in subgroups 100 km^{-1}); *g*(0) = the probability of detection on the trackline.

Stock	*f*(0)	*ESW*	CV	*E*(*s*)	CV	*n*/*L*	CV	*g*(0)	CV	Density	Abundance	CV
Pelagic	0.43	2.31	0.11	3.11	0.12	0.07	0.60	0.76	0.14	0.06	1,503	0.66
NWHI	0.43	2.31	0.11	3.11	0.12	0.15	1.04	0.76	0.14	0.13	552	1.09

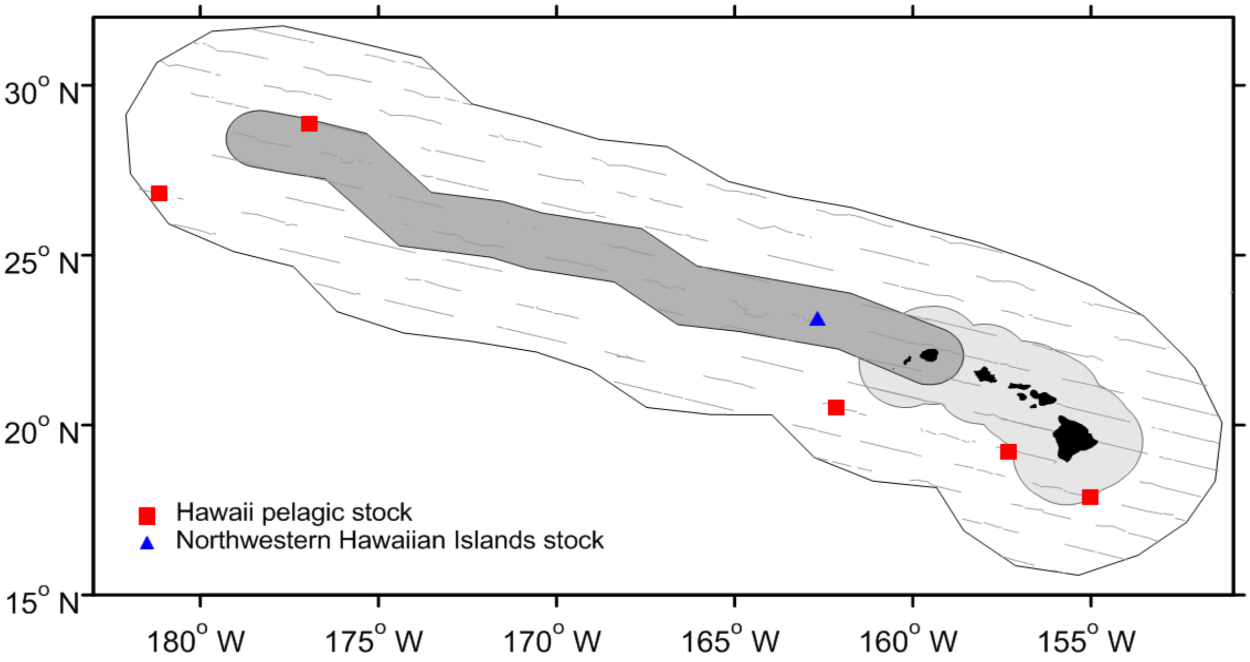

Figure 1.--Systematic-effort sightings of false killer whales from the Hawaii pelagic and Northwestern Hawaiian Islands stocks made during HICEAS 2010. The outer gray line represents the approximate boundary of the Hawaiian EEZ; the light gray region is the insular main Hawaiian Islands false killer whale stock area, including the overlap zone between the insular and pelagic false killer whale stocks; and the dark gray region is the Northwestern Hawaiian Islands stock area, which overlaps the pelagic false killer whale stock area and a portion of the insular main Hawaiian Islands false killer whale stock area. The fine lines depict systematic-effort survey coverage in Beaufort sea states from 0 to 6.

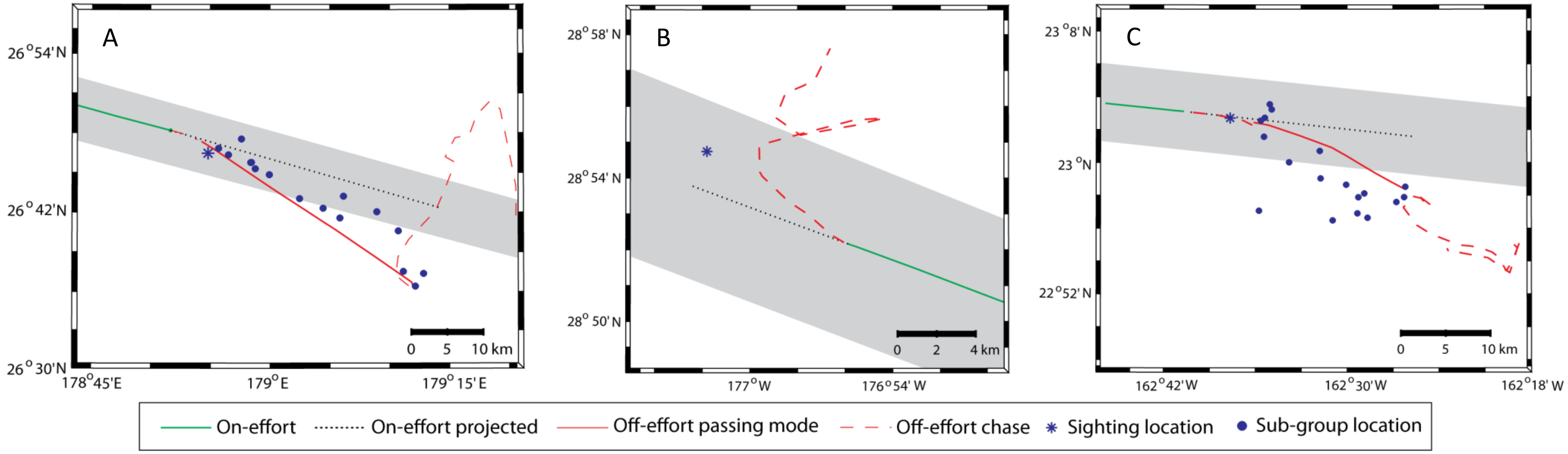

Figure 2.--Schematics of the systematic-effort false killer whales sightings for which the group-size estimation protocol was attempted: McII sightings 241 (A) and 35 (B) for the pelagic stock and OES sighting 86 (C) for the Northwestern Hawaiian Islands stock. The sighting location refers to the original visual detection that prompted the group-size estimation protocol. On-effort projected is the track the ship would have taken if systematic-effort status had been maintained. Off-effort passing mode represents the implementation of the group-size estimation protocol, with the localized subgroups shown as blue circles (except for McII sighting 35, as the protocol was not successfully executed). Off-effort chase is the track associated with approaching the group for photo-identification and biopsy sampling. The gray shading denotes the 4.5 km analytical truncation distance.

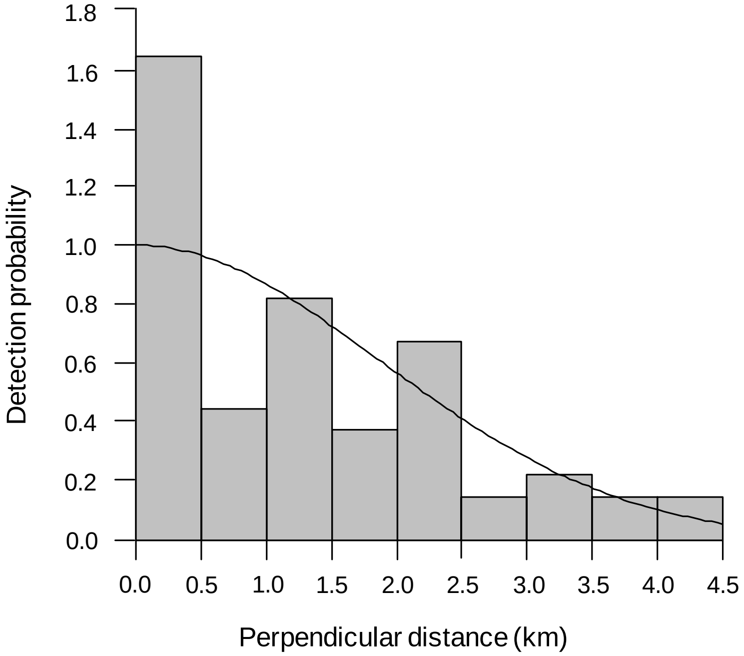

Figure 3.--Histogram of false killer whale sightings (*n* = 62) by perpendicular distance from the trackline and fit of the half-normal model used to estimate the detection function of subgroups.

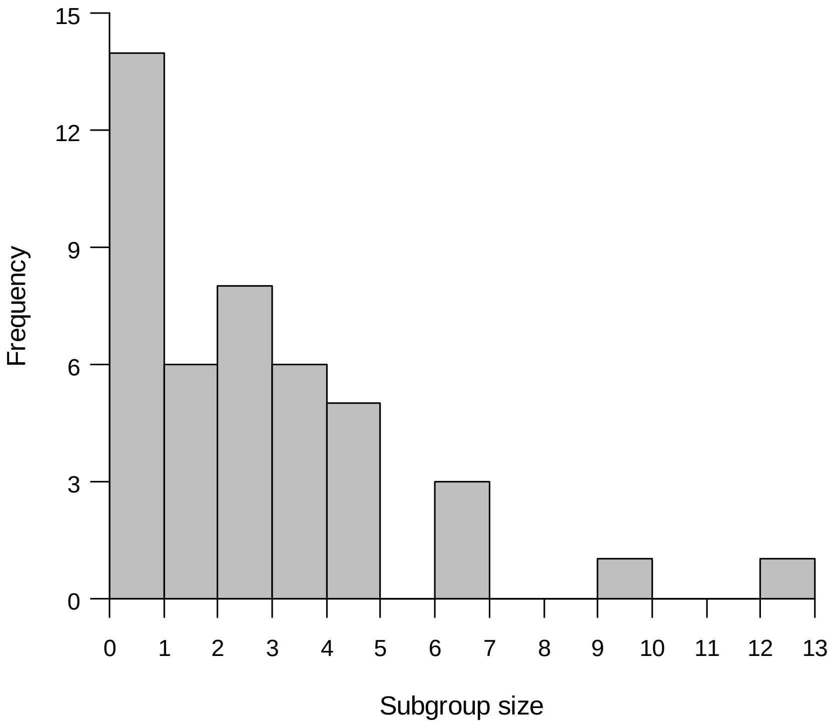

Figure 4.--Histogram of observed false killer whale subgroup sizes (*n* = 44) used in the estimation of expected subgroup size ($E(s)$ = 3.11, CV = 0.12).