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Using Haulout Data to Estimate Population Size for the Hawaiian Monk Seal

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ABSTRACT We describe a method for generating population estimates for monk seals at sites where the only available data were infrequent counts. The method relies upon the proportion of the non-pup population observed in standardized counts at other sites with known abundance. These proportions (p), compiled over all site and years having full population enumeration, were converted to haulout correction factors, where CF = $1/p$. These CFs were then applied to counts at sites with unknown population size to provide a bounded distribution of population estimates. A total of 2179 CFs were available from 44 site-years at intensively studied sites. These CFs were used for population estimation at two sites, Necker and Nihoa Islands, where infrequent counts had occurred and total abundance was unknown. The resulting population estimates

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(mean and 5/95 percentiles) indicated that abundance had increased at Nihoa from 2001 (mean 31 non-pups, 5/95%=21-47) to 2015 (mean 116, 5/95% = 79-177), but there was no increase evident at Necker. Method validation was conducted by randomly selecting 1-5 of the observed counts at site-years with full enumeration, applying the haulout correction factors to the observed count, and testing whether the true (known) value lay within the 5/95% range of the resulting distribution of estimates. When only one count was used, the method succeeded in capturing the true value in over 85% of 1000 randomizations for single islands and 65-87% of the randomizations in atolls. Performance markedly improved when >1 randomly selected count was used to estimate population size.

KEY WORDS correction factor, haulout, Hawaii, monk seal, Necker, Nihoa, population estimation

Estimating abundance of pinnipeds is complicated by the fact that these species alternate time spent hauled out on shore or ice with time at sea. As such, there is no time when the entire population is visible to be censused. Consequently, one approach often used to estimate abundance of seals is to expand counts of seals hauled out using correction factors (CF) to account for the proportion of seals at sea. The proportion of animals hauled out is often estimated using telemetry. For example, a sample of seals is fitted with VHF transmitters and the proportion of that sample found ashore during surveys is used to generate a CF (Yochem et al. 1987, Huber et al. 2001, Harvey and Goley 2011). Another CF-based approach is to use lifetable analysis to extrapolate from the observed count of one population segment, which can be most readily counted (generally pups), to the likely abundance of other classes (e.g., Pitcher et al. 2007, Lowry et al. 2014).

These standard CF approaches entail strong assumptions and considerable potential for bias. Telemetry-based studies, for example, implicitly assume that the sample of instrumented animals is representative of the population at large. Further, concerns about observational bias arise when the observation process for estimating CFs (telemetry) differs from the observation process (visual) for obtaining the counts to which the CFs are applied. Lifetable-based CFs typically involve the unrealistic assumption that the age structure of the population is constant.

The objective of this project was to develop a new population estimation procedure applicable to infrequently surveyed sites so that those sites could be incorporated into estimates of range wide monk seal abundance and trends. While the method we describe shares some elements in common with the traditional correction factor (CF) approaches described above, it differs in the manner in which the CFs were derived and applied, and in the fact that its performance can be validated using predictions at sites with known abundance.

STUDY AREA

The endangered Hawaiian monk seal is distributed throughout the Hawaiian archipelago with most of the population residing in the Northwestern Hawaiian Islands (NWHI), and a smaller, but growing population in the Main Hawaiian Islands (Figure 1). The abundance, demography and life history of the subpopulations in the NWHI are well documented through over 30 years of research (Ragen and Lavigne 1999, Antonelis et al 2006, Baker and Thompson 2007, Harting et al. 2007). Most of the research in the remote NWHI has been focused on the six subpopulations from Kure Atoll to French Frigate Shoals (Figure 1). In the MHI, population monitoring is largely supported by a network of volunteer observers who provide sightings of seals throughout the most accessible islands (Baker et al. 2011). Monk seal abundance at these thoroughly surveyed sites is estimated using either total enumeration of individually identifiable animals, closed capture-recapture methods, or minimum tallies (Baker 2004, Baker et al. 2006). There are, however, several sites inhabited by monk seals that, because of inaccessibility, logistics or other limitations, remain relatively understudied. Historically, the paucity of data from these sites, although not ideal, was not regarded as a major limitation to the overall assessment of the species' status, as these sites collectively comprised a negligible segment of the total abundance. More recently, as the abundance of seals in the NWHI has declined (Baker et al. 2011, Baker et al. 2013, Caretta et al. 2015), the status of the understudied sites, and their potential role in overall species recovery, is being reevaluated. With fewer total seals in the system, each occupied node in the species' range assumes greater significance.

Necker (Hawaiian name Mokumanamana) and Nihoa (Moku Manu) are small islands (19 ha and 69 ha, respectively) situated partway between the MHI and the NWHI (Figure 1). These islands are infrequently visited, with typically only 0-3 censuses (full counts in all suitable haulout habitat) per year conducted. To date, there has been very limited opportunity for individual seal identification such that population enumeration or capture-recapture estimation of abundance is not possible at these sites.

METHODS

At Necker and Nihoa, standardized counts are the only available data from which to derive abundance estimates. The link between individual counts and total population size is poorly understood (Eberhardt et al. 1999) and the number of seals varies greatly among individual surveys at a given site. Therefore, our approach is to characterize this relationship, in terms of the observed proportion of the population observed on counts, to derive estimates of abundance for Necker and Nihoa with associated uncertainty.

Standardized Counts

Seal counts were conducted by walking the entire perimeter of all single-island subpopulations (Necker, Nihoa, Laysan and Lisianski Islands), and all islands within atolls (French Frigate Shoals, Pearl and Hermes Reef, Midway and Kure Atolls) (Figure 1) and systematically searching for and documenting all animals on shore (Johanos 2015*a-c*). Seals seen in the water were excluded from counts. During these censuses, seal identity, sex, size class and location were recorded. Size classes included pups (young of the year), and non-pups (juveniles, subadults, and adults (Stone 1984)). Counts at multiple-islet atolls were completed in two days or less, whereas single-island counts were always completed within the day.

Unlike in many pinnipeds, parturition in Hawaiian monk seals is asynchronous with a broad peak from March to August (Johanos et al 1994). However, because survival to weaning is typically well over 90% and weaned pups tend to spend most of their time on shore for approximately two months post-weaning, a fairly complete count of annual pup production can be obtained from a few ground surveys, particularly if they are conducted in late summer, when most have been born but have not yet begun spending much time at sea. In this paper, we focus on estimating the abundance of non-pups, which is less tractable than tallying pups because these older seals are often at sea. Further, we do not estimate pup abundance using correction factors because the pup "population" is not closed, as the total number of pups changes with births during the period when counts are conducted. In contrast, the non-pup population is treated as effectively closed for our purposes, and we do not attempt to correct for the low rate of interatoll movements that is known to occur (Johanos et al. 2014).

Haulout Correction Factors

Our strategy for estimating population size from partial counts was to capitalize on the information contained in the historical data collected at thoroughly studied sites to help infer what segment of the total non-pup population was likely to be observed on comparable counts at sites with less complete information (Necker and Nihoa Islands). Specifically, we used the proportion of the total non-pup population that was observed on counts. For each site-year combination where full enumeration of non-pups was achieved as determined by examination of seal discovery curves (criteria presented in Baker et al. 2006), the proportion, *p*, of the total non-pups observed on each complete count can be determined. We refer to the inverse of that proportion, *1/p*, as a "haulout correction factor" (CF).

Whereas the proportion hauled out is simple to calculate for sites where the population has been enumerated, it is an unknown quantity when the total number of seals is not known. Here, we reference the CFs observed at other sites to estimate the total abundance for the unknown populations. We assume the range of variability in CFs observed among all accumulated counts from populations where the non-pup abundance was known also encompasses the haulout proportion at Necker and Nihoa Islands. By preserving the full range of that variability when generating our population estimates for the unknown populations, we are able to estimate not only mean population size, but also uncertainty around that point estimate. Our method requires that the season-long compilation of non-pups be complete and therefore we used only those CFs associated with full enumeration site-years. The total number of CFs is then the total number of counts conducted at all site-years with full enumeration.

Population Estimation

The number of non-pups observed during each count at Necker/Nihoa was used as the base value for generating random population estimates. This was done by applying each of the observed haulout correction factors obtained from the other NWHI sites to the annual mean count for Necker/Nihoa, thereby generating a set of N population estimates for each year. The mean, 5% and 95% percentiles of this population estimate distribution were then determined. Because pups are not included in the resulting estimate, the number of pups must be determined separately from the cumulative number of distinct individuals (based on timing, markings or other factors) observed on one or more surveys.

Method Validation

To validate the procedure described above, we evaluated how well the population estimation process performed for site-years with known abundance. For this test, only the correction factors collected from sites other than the one being validated were used for population estimation, thereby simulating the condition where the only data available for a site were the counts, and the corresponding (same-site) correction factors were lacking. We also tested the benefits associated with having more than one count for population estimation by randomly selecting multiple counts and using the mean from those counts as the base for applying the correction factors. For each random set (n=1000 random sets of counts), the entire set of CFs from other sites were applied to produce a distribution of possible population estimates. Although the number of randomizations was fixed at 1000 for all site-years, the number of distinct perturbations (unique combinations of counts) was less than 1000 for site-years having small numbers of counts. Each distribution was then examined to determine a) whether the true value was contained in the 5/95% range of the distribution and b) the location (percentile) of the true value in the distribution. For each site-year, the proportion of randomizations that were successfully "validated" (i.e., the first criteria was satisfied) served as the primary metric for assessing how well the haulout-based estimation process performed.

RESULTS

NWHI Counts and Non-Pup CFs

A summary of counts conducted at the six main NWHI breeding sites (N=4379) are given in Table 1. Although a minimum of 8 counts were conducted at most sites since the late-1990s, many were not accompanied by full population enumeration in the same year and consequently the non-pup CFs from those counts could not be used for population estimation. A total of 2179 qualifying counts occurred during 44 full-enumeration site-years at five different sites. There were no full enumeration years at French Frigate Shoals, only one at Pearl and Hermes Reef and three at Kure Atoll. The majority of the counts accepted for the analysis were therefore from Laysan Island (N=1001 counts), Lisianski Island (N=902) and Midway Atoll (N=231).

The proportion of the non-pup population observed during each of the 2179 counts, and hence also the corresponding correction factors, varied among sites and across years (Figure 2). In general, the mean CFs fell in the 3.0-4.0 range.

Combining all six sites (upper left plot in Figure 2), it is evident that both the mean and the range of the CFs varied significantly across years [one-way ANOVA: $F_{1,22} = 11.587$; $p < 0.001$]. The overall mean (all sites and years combined) was 3.40 (s=0.996), equating to 0.29 of the non-pup population observed on an average count. The distribution of CFs (Figure 3) is strongly right-skewed (Pearson's skewness coefficient = 2.32) as expected with a left-bounded distribution, although some of the low counts contributing to the rightmost bins are suspect and may represent partial counts that failed to record all seals present on the beach.

Population Estimation

The distribution of 2179 CFs were used to estimate the annual non-pup population at Necker and Nihoa Islands. The resulting population estimates are given in Figures 4a-4b. The mean non-pup population estimate for Necker was 53 seals (range 24-95), and for Nihoa it was 87 seals (range 31-127). Although there appear to be some periods of increase or decrease at Necker (most notably 4 consecutive increases from 2006-2009), there was no distinct overall trend from 1996-2013. In contrast, at Nihoa, the mean population estimate reflects a generally increasing trend from 2001-2015. A linear regression fit to only those years was significant (slope = 4.43, $F_{1,13}$= 14.431, p=.002).

Validation of Population Estimation Procedure

Using only one count to estimate the population size on single islands (Laysan and Lisianski Islands), the true value (observed number of non-pups in the population) was contained within the 5%/95% region of the estimate distribution for more than 85% of the 1000 randomizations (Figure 5) for each site-year. However, at the atolls, the proportion of the randomizations that met this validation criteria dropped to ~65-87% for most site-years (lower, dotted line in Figure 5).

Performance of the haulout correction methodology was progressively improved by increasing the number of counts that was used as the basis for the estimation. For example, for single islands, when using the mean number from 5 counts, nearly all of the randomizations successfully captured the true value in the 05/95% range of the estimates, and the performance with 5 counts was only slightly lower for the atolls (upper line in Figure 5).

DISCUSSION

The method described herein provides the first systematic effort to derive population estimates for sites in the monk seal's range where intensive research has yet to be conducted, and for which the only available data consists of infrequent counts collected opportunistically as feasible. Previously, the paucity of data for these under sampled sites has hampered our ability to provide a comprehensive assessment of the overall species status unencumbered by multiple caveats and qualifiers.

It is important that we were able to attach confidence estimates (expressed as .05/.95 percentiles) to our point estimates because we recognize that the count data do not enable a precise estimate of total abundance. Prior work (Eberhardt et al. 1999) found that the relationship between the counts and the population size was unpredictable and, lacking a functional model or auxiliary data to link the two measures, the counts alone did not provide a reliable index of the year-to-year population trend over short time frames, but did do so when evaluated in the long term. This is an important observation but, because our method is not intended to deliver a precise point estimate of abundance, but rather a range of estimates that contains the actual value, the fact that the counts fail to recapitulate the observed year-to-year fluctuations in total population size does not negate the value of our results. For example, it is noteworthy that in 8 of the last 9 years, the lower 5%iles of our Nihoa estimates exceeds the 95%iles of the 2001-2002 estimates, lending strong support to the conclusion that the number of seals using this site had indeed grown.

The principal advantage of our method as compared to more traditional means of deriving CFs, is that we were able to directly measure the proportion observed on the beach in populations of known size, thereby circumventing some of the assumptions inherent to other methods. For example, unlike telemetry-based CFs, the observation process for estimating monk seal CFs is identical to the observation process for obtaining the statistic (mean abundance on counts) that is corrected. Further, our estimation relied on a very high number of replicates (N=2179) obtained from counts for full enumeration site-years at five different subpopulations over more than 30 years. This is an important distinction as compared to alternatives such as using the proportion of radio-tagged seals found ashore during a small number of separate or concurrent beach counts and aerial surveys (e.g., Yochem et al. 1987, Huber et al. 2001, Harvey and Goley 2011). In aggregate, the distribution of CFs were representative of a broad range of survey conditions rather than providing a short-term temporal snapshot of conditions which might or might not be representative of the new site.

The greatest uncertainty with our approach is whether the haulout pattern at the unknown site conforms to the aggregate of the sites contributing to the set of CFs. Barring any information that might suggest otherwise, we believe that is a reasonable assumption, while recognizing that we must be attentive for any evidence to the contrary.

In our analysis, we have not endeavored to probe the ecological context or diagnose the key biological drivers that contribute to the within-year, between-year, or inter-site variability in haulout proportions. Such factors as prey availability, seal condition, presence of predators and competitors (both intraspecific and interspecific), biological status (e.g., pregnant, lactating or molting), time-of-day, weather, tides, available haulout space are likely to all influence the frequency and amount of time that seals haulout and are "captured" in counts (see, for example, Brown and Mate 1984, Stewart 1984, Kelly 2005). A better understanding of how those factors affect monk seal haulout patterns, and their role and relative importance at different sites and years, might allow us to better estimate the range of CFs that are most applicable to the prevailing conditions at a specific site and year, thereby reducing the confidence limits around our estimates. Such adjustments have been used to refine haulout correction factors in other species (e.g., Thompson and Harwood 1990, Frost et al. 1999). However, the utility of such relationships, even if they could be identified and fully characterized at intensively studied sites, would be limited for estimating abundance of different sites where information about most or all the potentially key covariates were lacking..

Our validation test indicated that our method performed acceptably well in capturing the true value within the range of estimates. However, the estimates were marginally less reliable in the three atolls (Pearl and Hermes Reef, Midway and Kure Atolls) as compared to the single islands (Laysan and Lisianski Islands) (Figure 5). The performance of the estimation procedure was greatly improved as the number of counts was increased from 1 to 5, but the difference was most striking between using one count and using a mean from 2 counts (Figure 5). The observed improvement when using multiple counts is intuitively consistent with the expectation that greater numbers of counts should provide a better representation of the “normal” proportion of the population present on the beach. In contrast, a single count could be an anomalous value due to any number of factors. This observation has direct bearing on field logistics and planning as it reinforces the need to obtain more than one count at a site if it is at all feasible given other considerations.

MANAGEMENT IMPLICATIONS

The methodology we describe, which uses a range of correction factors to estimate total population size from the number observed on the beach during standardized counts, provides a means for generating population estimates when more complete data are lacking. The resulting estimates may be iteratively refined or adjusted as additional data are acquired for the site in question. For the monk seal, this represents a significant advancement because it enables us to provide a more complete estimate of the total species abundance and better assess the relative importance of different regions of the monk seals’ range to the overall recovery initiative.

We have emphasized application of this method to Necker and Nihoa Islands, but it could be used to generate population estimates for any of the other six NWHI sites, should field effort be reduced due to limited funding, shifting priorities, or logistical constraints. Also, while all of the counts used to produce the CFs used herein were conducted in the traditional way (i.e., human observers traversing the beach), at least two new technologies – deployment of time-lapse cameras and surveys by unmanned aircraft – are currently being tested to augment the survey data for infrequently visited sites. With sufficient coverage of the available haulout habitat on each site, data emanating from these methods should be comparable to that of the traditional counts and compatible with our methodology.

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Figure 1. The Hawaiian Archipelago, depicting the two main regions of the monk seal range: The Northwestern Hawaiian Islands NWHI) and the Main Hawaiian Islands (MHI). Necker and Nihoa Islands lie near the interface between the NWHI and MHI.

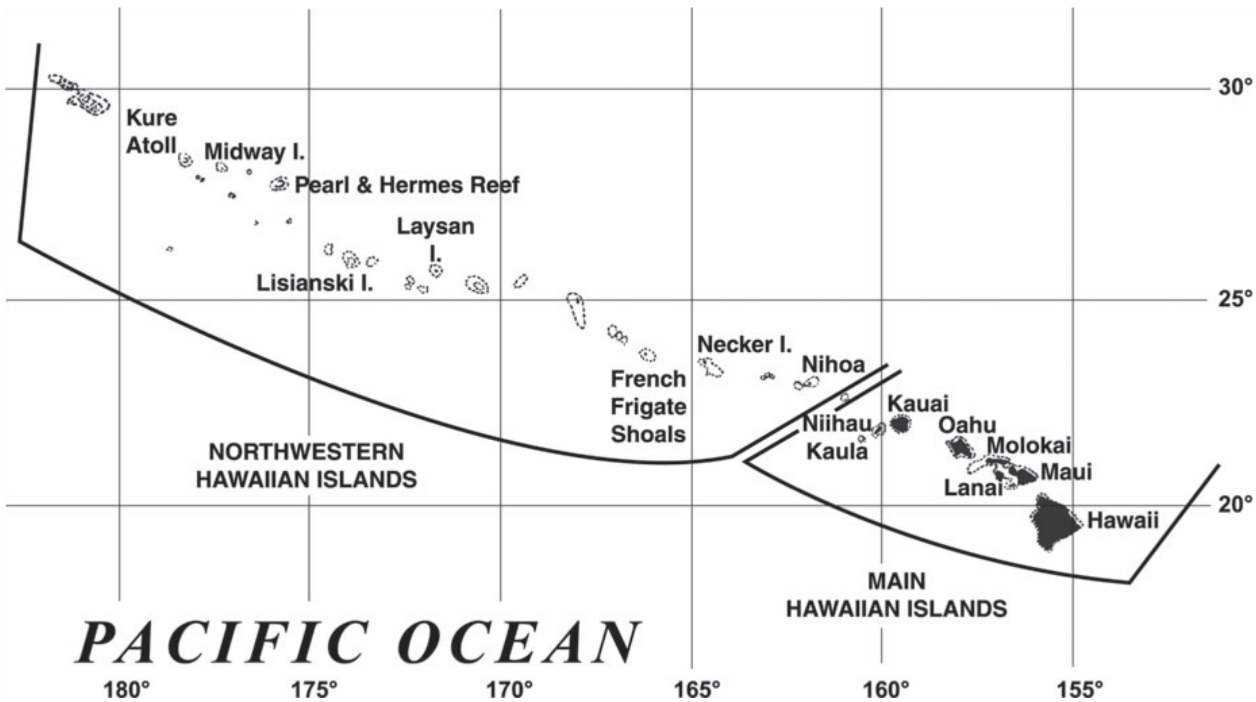


Figure 2. Non-pup correction factors (CFs) for beach counts in full-enumeration years (1983-2014) at five NWHI sites (no qualifying years at French Frigate Shoals). Plot icons depict mean (center), ± 2 SD (whiskers). Larger CFs equate to a smaller proportion of the non-pup population observed on the counts. Conversely, small CFs equate to a greater proportion of the non-pup population observed. The overall mean (3.40) is indicated by a dotted line in the all sites combined plot (upper left).

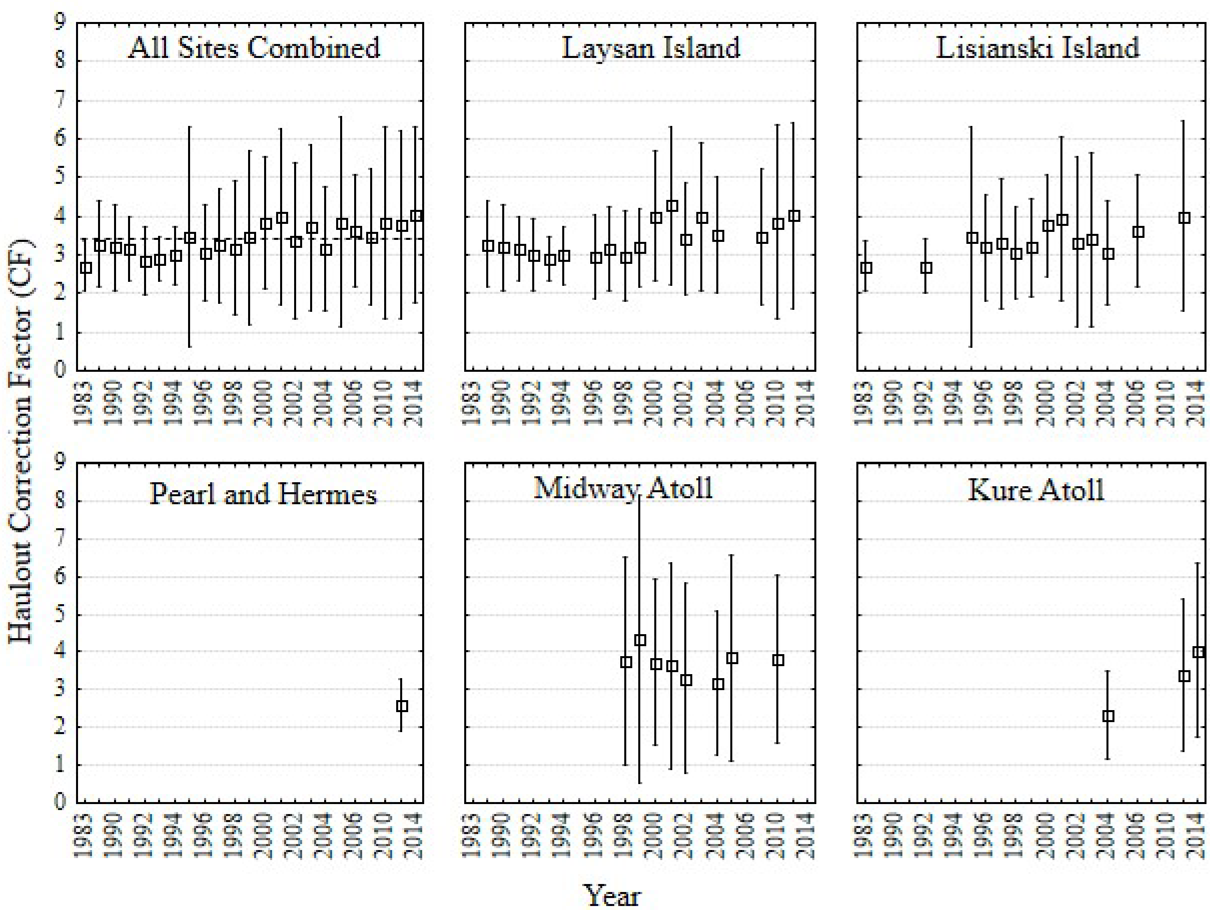


Figure 3. Distribution of non-pup correction factors for full enumeration years (1983-2014) with all NWHI sites combined.

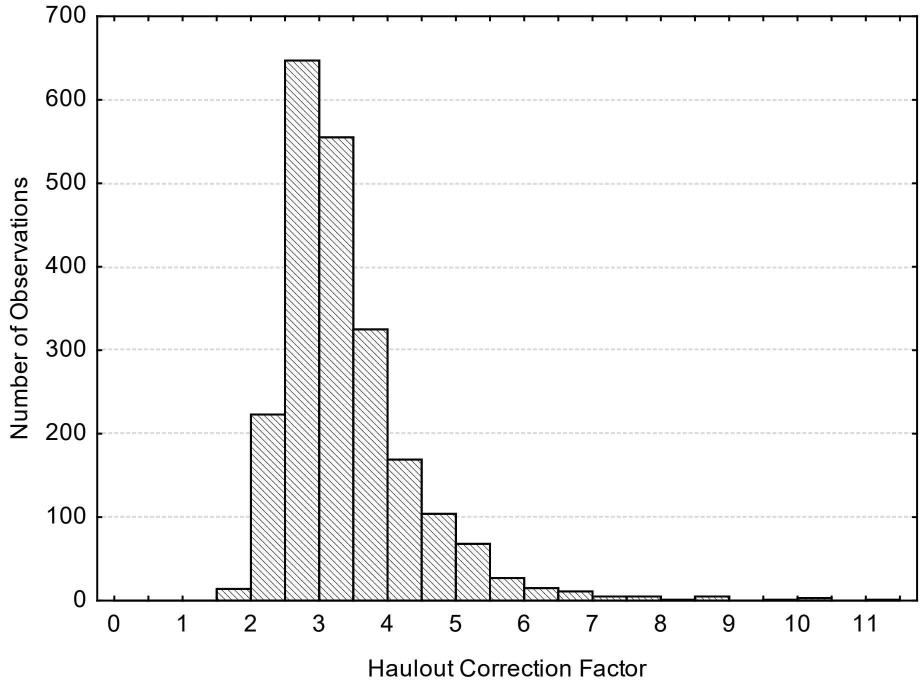
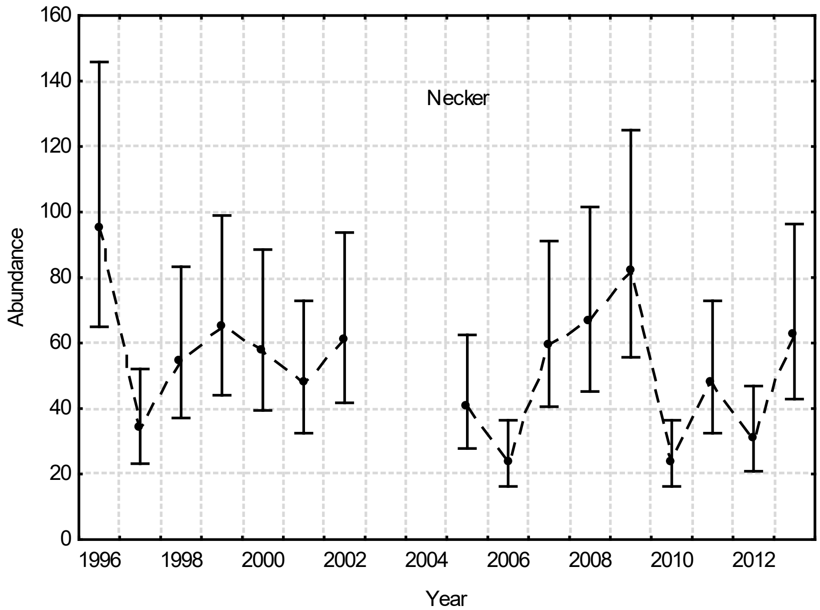


Figure 4a-4b. Non-pup population estimates at Necker and Nihoa Islands (mean and 5/95 percentiles) as derived from observed haulout proportions at other NWHI sites.



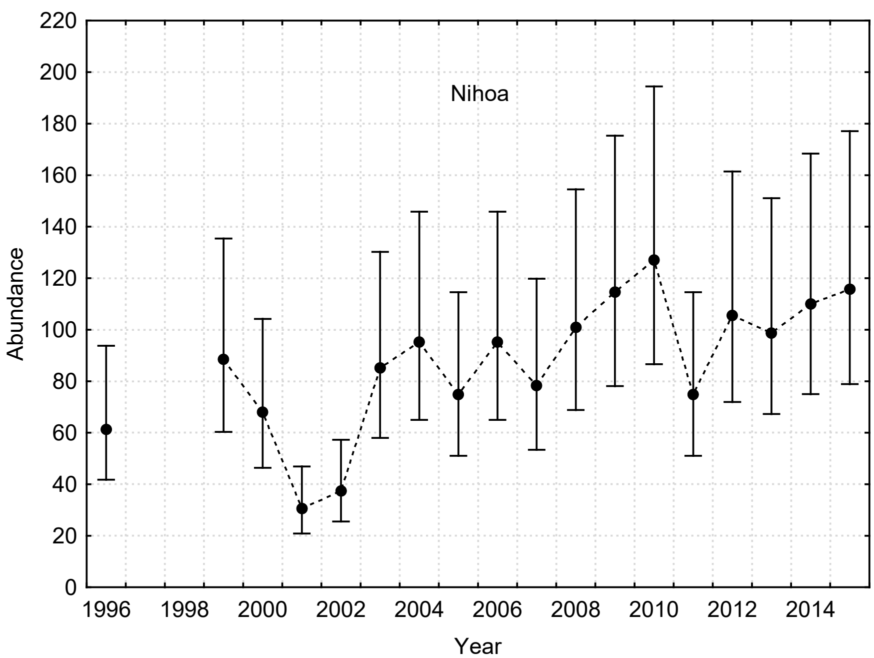


Figure 5. Proportion of randomizations (N=1000) for which the known population size fell within the 05/95% region of the distribution of population estimates derived by applying haulout corrections from other sites. Separate lines display results (proportion of randomizations that met validation criteria) when >1 beach count was used to produce the population estimate.

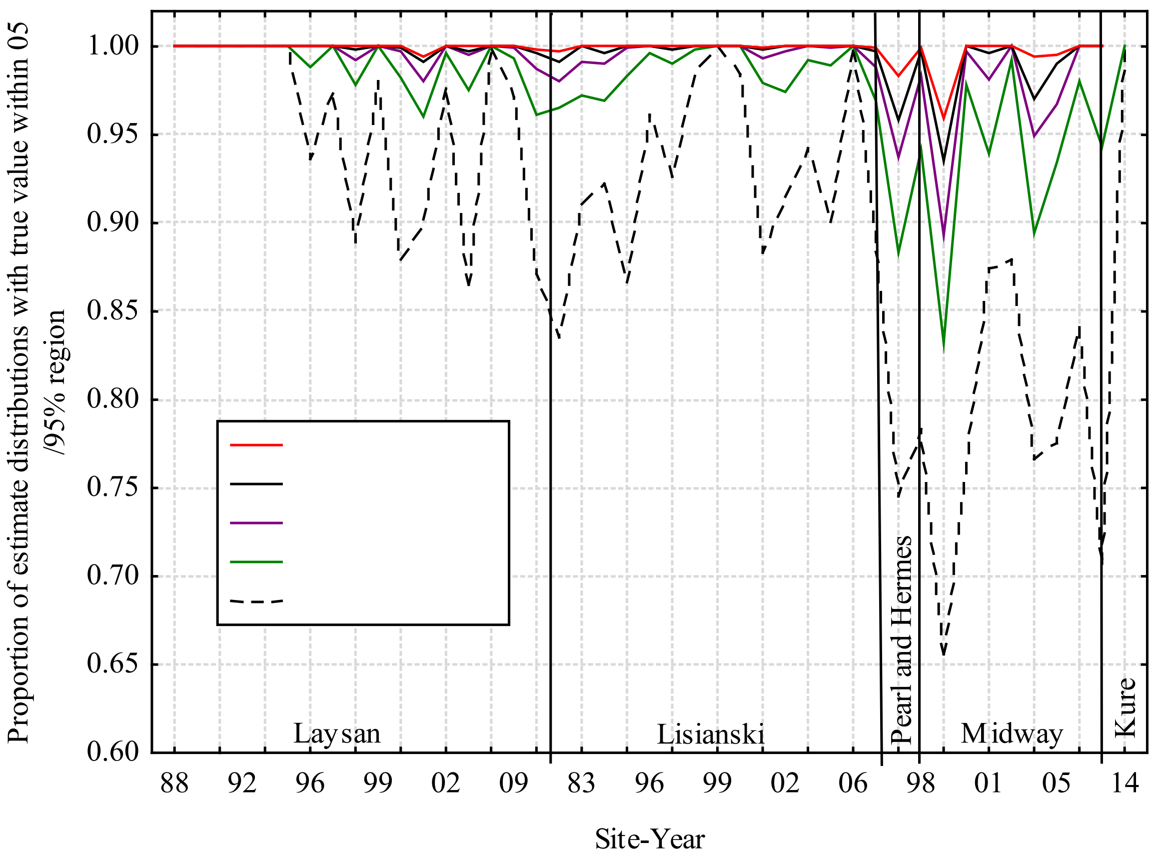


Table 1. Number of historic beach counts at main NWHI sites, 1983-2014, with sites + years with full population enumeration indicated. The total number of counts at each site and number of counts for full enumeration years are given in the bottom rows.

	Site					
	French Frigate	Laysan	Lisianski	Pearl and Hermes	Midway	Kure
1983		24	52[a]	5		33
1984		45	16	5		52
1985	9	86	15	1		79
1986	3	20	10	6		15
1987	9	26	11	11		62
1988	8	33[a]		14		54
1989	15	26		8		54
1990	10	39[a]	22	1		50
1991	10	37[a]	12	11		44
1992	11	27[a]	28[a]	5	12	15
1993	16	10[a]	13	4	1	15
1994	10	20[a]				8
1995	10	53	76[a]	10	9	12
1996	10	121[a]	102[a]	8	11	15
1997	10	63[a]	91[a]	9	28	9
1998	10	102[a]	95[a]	8	52[a]	10
1999	10	84[a]	93[a]	8	50[a]	10

2000	7	45[a]	45[a]	10	27[a]	13
2001	17	46[a]	56[a]	8	25[a]	12
2002	10	43[a]	78[a]	8	18[a]	14
2003	10	51[a]	46[a]	6	8	11
2004	14	39[a]	47[a]	10	26[a]	11[a]
2005	13	30	43	11	20[a]	14
2006	11	15	41[a]	14	13	12
2007	16	32	10	15	27	18
2008	20	18	11	2	7	12
2009	25	63[a]	32	17	14	12
2010	24	102[a]	31	13	13[a]	19
2011	33	76[a]	52[a]	25[a]	12	7[a]
2012	12	17	14	10	9	3
2013	21	23	12	10	7	4
2014	21	15	14	6	6	2[a]
Tot Cnts.	405	1431	1168	279	395	701
Full Enum	0	1001	902	25	231	20

[a] Indicates full enumeration years used for deriving correction factors