Estimating Hawaiian monk seal range-wide abundance and associated uncertainty

Jason D. Baker[1,]***, Albert L. Harting**[2]**, Thea C. Johanos**[1]**, Charles L. Littnan**[1]

[1]**Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA, 1845 Wasp Blvd #176, Honolulu, Hawaii 96818, USA**

[2]**Harting Biological Consulting, 8898 Sandy Creek Lane, Bozeman, Montana 59715, USA**

ABSTRACT: The type and quantity of survey data, and consequently, applicable methods for estimating abundance, vary throughout the range of the Endangered Hawaiian monk seal *Neomonachus schauinslandi*. Here we present a new approach to combine disparate data and methods to estimate the range-wide abundance of this species, along with associated uncertainty. We quantified subpopulation abundance using total enumeration, closed population capture-recapture methods, empirically derived relationships between survey effort and proportion of the population detected, minimum tallies, or standardized land surveys corrected to account for seals in the water. We used a Monte Carlo approximation to generate a distribution of range-wide abundance, by summing randomly drawn values from distributions of site-specific abundance. Data to estimate range-wide abundance were available for 2013, 2014, and 2015; our estimates were 1291, 1309, and 1324 individuals, respectively. Although the point estimates increased over 2 yr, the confidence intervals for all estimates overlapped. We recognize that these estimates are subject to some varying degree of negative bias, which precludes drawing unequivocal conclusions regarding current population trends. However, after a prolonged history of population decline in this species, the lack of evidence for further decline during 2013 to 2015 is encouraging. Additional years of consistent monitoring will enable reliable assessment of the trend in total Hawaiian monk seal abundance.

KEY WORDS: *Neomonachus schauinslandi* · Abundance estimation · Population trend · Monte Carlo

INTRODUCTION

The Endangered Hawaiian monk seal *Neomonachus schauinslandi* metapopulation (Littnan et al. 2015) comprises multiple subpopulations distributed throughout the 2600 km wide Hawaiian Archipelago (Fig. 1). Total abundance and trends are important metrics for conservation, but estimating these parameters for the monk seal has been hampered by the logistical, analytical, and funding constraints associated with surveying a sparsely distributed species over such a vast range. From the mid- to late 20th century, standardized counts at the subpopulations from Kure Atoll to French Frigate Shoals (Fig. 1) provided an adequate index of overall trends in abundance (although not actual abundance), because the preponderance of seals resided within that portion of the species' range (Ragen & Lavigne 1999).

Over the past 3 decades, the number of monk seals (as indicated by mean standardized counts) from Kure Atoll to French Frigate Shoals has declined by approximately 50% (Johanos 2015a). During the same period and probably beginning previously, monk seals have been re-colonizing the main Hawaiian Islands (Ni'ihau to Hawaii Island), from which they had likely been extirpated following the arrival
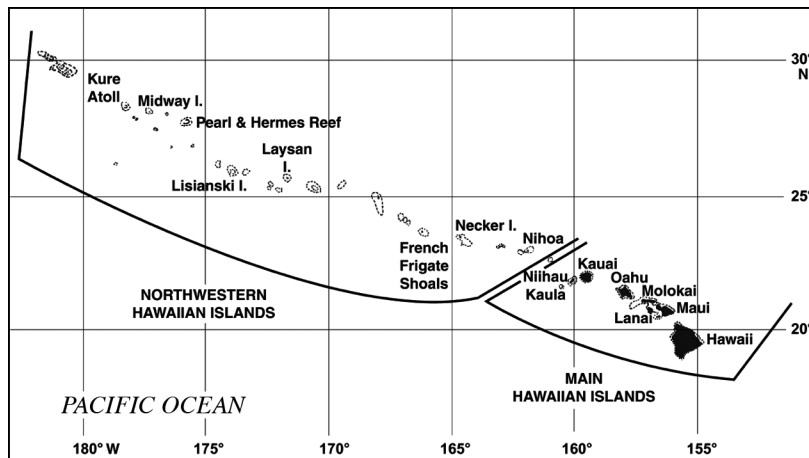
Fig. 1. Hawaiian Archipelago and range of the Hawaiian monk seal *Neomonachus schauinslandi*. Dotted lines show 100 m bathymetric contours

of Polynesians some 800 yr ago (Baker & Johanos 2004, Baker et al. 2011, Wilmshurst et al. 2011). Additionally, monk seals reside on 2 relatively inaccessible islands, Necker and Nihoa (Fig. 1), where standardized counts suggest that abundance has recently been relatively stable and apparently increasing, respectively (Johanos 2015a, A. L. Harting et al. unpubl.). These significant changes in both abundance and distribution of Hawaiian monk seals have rendered the traditional method of characterizing abundance based on only a portion of the range unreliable. Furthermore, the type and quantity of survey data, and consequently, applicable methods for estimating abundance, vary throughout the monk seal's range. Here, we present a new approach to combine disparate data and methods to estimate the range-wide abundance of this species, along with associated uncertainty.

MATERIALS AND METHODS

Estimating subpopulation abundance

Abundance of monk seals at individual subpopulations is variously estimated based on the type, quantity, and quality of available data. In general, pups are the most tractable age class to survey. Unlike in many pinnipeds, parturition in Hawaiian monk seals is asynchronous, with a broad peak from March to August (Johanos et al. 1994). However, survival to weaning is typically over 90%, and weaned pups tend to spend most of their time on shore for approximately 2 mo post-weaning (Gilmartin et al. 1993, Hiruki et al. 1993). Thus, a fairly complete count of

annual pup production can be obtained from a few well-timed ground surveys, particularly if they are conducted in late summer, when most pups have been born but have not yet begun spending much time at sea (Henderson & Johanos 1988). The exception is that Galapagos shark predation at French Frigate Shoals has reduced survival to weaning to less than 75% in some years (Gobush & Farry 2012). However, duration of field seasons at this site has been consistently sufficient to document the total pups born, including subsequent mortalities. In contrast to tallying pup production, estimating the number of seals older than pups (hereafter referred to as non-pups) is more challenging. Non-pups alternate between foraging at sea and spending time on shore to rest, molt, and, for adult females, to give birth and nurse their young.

Annual field camps are established during late spring to late summer at the 6 subpopulations from Kure Atoll to French Frigate Shoals. Field camp timing varies, but largely overlaps among sites. Camps range from a few weeks to many months in duration, during which staff conduct population research and monitoring, and also undertake numerous conservation actions that yield population benefits (Harting et al. 2014). Historically, each subpopulation has hosted from <100 up to a few hundred seals. Field researchers conduct regular surveys of island and atoll shorelines where they identify individual seals using plastic flipper tags, applied pelage bleach marks, natural scars, and other marks (Harting et al. 2004). At these sites, pup production is assessed by individually identifying all pups present during the field season.

Baker et al. (2006) analyzed discovery curves (accumulation of sightings of new individuals over time during a field season), and determined that all non-pups in a subpopulation could be considered identified if 100 h of survey effort were expended without finding a new individual. Where such total enumeration is not achieved, closed capture-recapture estimates generated with Program CAPTURE are used (Otis et al. 1978, White et al. 1982, Rexstad & Burnham 1991, Baker 2004). However, sometimes no appropriate estimator is obtainable using Program CAPTURE (i.e. the model selection criterion is <0.75, following Otis et al. 1978) or the estimates are less than the known minimum abundance as described by Baker (2004). For such cases, we developed a new

estimation method that uses site-specific empirical relationships between survey effort and the proportion of the population identified to adjust minimum counts. Using discovery curves constructed as described by Baker et al. (2006), we calculated the proportions of the non-pup population identified versus the number of survey effort hours expended for a set of reference years when total enumeration was achieved at a given site (Fig. 2). These observations are the basis for estimating the likely proportion of seals that had been identified in years when field seasons ended before all were detected. For example, a total of 99, 206, and 324 survey effort hours were expended searching for seals at Lisianski Island in 2013 to 2015, respectively, and the criterion for achieving total enumeration was not met in any of those years. Density histograms of the proportion of the population identified in reference years at these same time points can be extracted (inset graphs, Fig. 2). Probability distributions fitted to these histograms (solid curves in Fig. 2) were sampled to provide corrections to minimum counts (details in subsequent section). We fitted beta distributions because the beta function is highly flexible and bounded by 0 and 1. We used the package fitdistrplus in R to fit the beta distributions (Delignette-Muller & Dutang 2015). We prefer capture-recapture estimates derived from Program CAPTURE over estimating the proportion identified using discovery curves because the former is a well-established analytical method, whereas the latter is an empirical approach that necessarily relies on sparse reference data at some subpopulations. However, when a capture-recapture estimate is not obtainable, discovery curve analysis is an acceptable alternative.

Necker and Nihoa Islands are small (<1 km^2), isolated, steep-sided basalt volcanic remnants (Evenhuis & Eldredge 2004). They are ecologically and culturally sensitive, and difficult to safely land on with small boats. Consequently, systematic monk seal surveys typically only occur from 0 to 2 times per year at these sites. This level of effort is insufficient for total population enumeration, capture-recapture abundance estimation, or discovery curve analysis. Here we estimated non-pup abundance using the empirical distribution of the ratio of beach counts to total population size at other Northwestern Hawaiian Islands subpopulations to correct standardized counts at Necker and Nihoa Islands for the proportion of seals at sea (A.L. Harting et al. unpubl.). Standardized counts consist of researchers systematically counting all seals on all shorelines of an island within a several-hour period. Pup production at Necker and Nihoa Islands was estimated as the mean of the annual total pups observed during the past 5 yr, excluding counts occurring early in the pupping season when most have yet to be born. It is unlikely that all the pups born are detected during 1 or 2 d of survey effort, and the proportion counted varies year to year. The 5 yr mean was used simply to reduce the sensitivity of a single year's count to bias. In years when sufficient effort was expended to give confidence that the pup count is relatively reliable, that single year count would be used instead of the 5 yr mean.

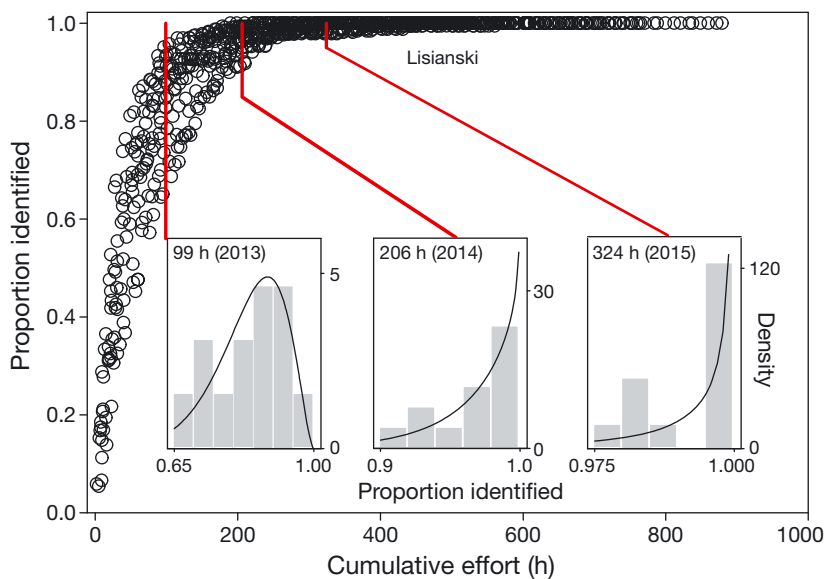The monk seal subpopulations described thus far are all associated with

Fig. 2. Demonstration of method for characterizing the proportion of the total non-pup Hawaiian monk seal *Neomonachus schauinslandi* population counted in years when field effort was of insufficient duration to identify all seals. Main graph shows the known proportion of the non-pup population (open circles) identified, plotted against daily cumulative field survey effort based upon 13 reference years when the total population at Lisianski Island had been enumerated. In 2013 to 2015, a total of 99, 206, and 324 h of survey effort were expended, respectively, which was insufficient to conclude that total enumeration had been achieved. Proportions of the total identified in each reference year at these effort time points (vertical red lines) are shown (grey bars) in the 3 inset probability density histograms. Abundance distributions (included in Figs. S2–S4 in the Supplement at www.int-res.com/articles/suppl/n031p317_supp.pdf) were generated by dividing the total number of seals counted in each year by 30 000 randomly sampled proportions from beta distributions fitted to the observed proportions (black lines in inset graphs)

the small islands and atolls of the remote North-western Hawaiian Islands (from Kure to Nihoa, Fig. 1). In contrast, the main Hawaiian Islands (Ni'ihau to Hawaii Island) include 8 relatively large high islands and several offshore volcanic remnants, islets, and stacks. This region of Hawaii is home to approximately 1.4 million residents (http://quickfacts. census.gov/qfd/states/15000.html) and is visited by more than 8 million people annually (http://files. hawaii.gov/dbedt/visitor/visitor-research/2014-annual-visitor.pdf). In the main Hawaiian Islands, infor-mation on seal sightings is reported throughout the year by a variety of sources, including a volunteer network, the public, and directed observation effort by the US National Marine Fisheries Service (NMFS) (Baker et al. 2011). This system tends to effectively identify (again, using tags and natural and applied pelage marks) most of the seals using Kauai, Oahu, Molokai, Maui, and Hawaii Island. Seals at Lanai and Kahoolawe are likely undercounted, although it is believed that these sites host a relatively small por-tion of the total main Hawaiian Islands population. Thus, from Kauai to Hawaii Island, the total number of individual seals identified in a calendar year is considered the best available estimate of abundance for this region.

In contrast, relatively large numbers of monk seals occur on the islands of Ni'ihau, Lehua, and Ka'ula Rock, which are relatively inaccessible and histori-cally have been rarely surveyed. Since 2013, a small number of surveys of privately owned Ni'ihau Island and nearby Lehua Island have been conducted col-laboratively between NMFS, Ni'ihau residents, and the US Navy. These surveys constitute standardized counts analogous to those conducted on Necker and Nihoa Islands, which are corrected for the proportion at sea (A. L. Harting et al. unpubl.). However, Ni'ihau is a much larger island, so that counts are conducted by multiple teams on foot, horseback, in small boats, and using a helicopter to survey all shorelines within a day. There are well-documented differences in ter-restrial and marine habitats, piscivorous fish popula-tions, and monk seal foraging behavior between the Northwestern and main Hawaiian Islands (Parrish et al. 2008, Baker et al. 2011, Cahoon 2011, Cahoon et al. 2013). Because these differences could influence the proportion of time seals spend at sea, we chose not to use correction factors derived using Northwest-ern Hawaiians Islands data (A. L. Harting et al. un-publ.) to correct standardized counts in the main Hawaiian Islands. Consistent with this, a recent telemetry study (Wilson et al. in press) found that main Hawaiian Islands monk seals (N = 23) spent a

greater proportion of time ashore (mean = 0.37) than A. L. Harting et al. (unpubl.) estimated for Northwest-ern Hawaiian Islands seals (mean = 0.29). Therefore, we calculated the total non-pup estimate for Ni'ihau and Lehua Islands as the mean total count at those sites divided by the mean proportion of time on shore in the main Hawaiian Islands (Wilson et al. in press). The total pups observed at Ni'ihau and Lehua Islands during surveys conducted sufficiently late in the year to encompass the majority of the pupping season were added to obtain total estimated abundance for these sites.

Estimating range-wide abundance

We derived total abundance of Hawaiian monk seals from the site-specific estimates obtained using the various methods described above applied to Hawaiian monk seal population data (Johanos et al. 2015a,b). Monk seals move among islands through-out their range, and the likelihood of movement is inversely related to the distance between islands (Johanos et al. 2014). Some seals are seen in more than 1 subpopulation within a single year. To avoid double-counting such individuals, we assigned each seal to a single subpopulation. In this way, discrete subpopulation abundance estimates (regardless of the method by which they were generated) are based only on the individual seals that are assigned to the various sites.

By convention, the main Hawaiian Islands are treated as a single subpopulation because the islands are relatively close to one another and seals readily move among them (Johanos et al. 2014, Lopez et al. 2014). To avoid double-counting and over-amplifying the estimated number of non-pups, we based the cal-culation of abundance for Ni'ihau and Lehua Islands on the total count of non-pups at those sites less any identified individuals who were seen (and already counted) elsewhere during the same calendar year.

Estimating the distribution and confidence limits of total abundance

To evaluate uncertainty in total range-wide monk seal abundance, we used estimates of error associ-ated with site-specific abundance estimates. Some of those estimates were necessarily treated as invariant, including sites where total enumeration was achieved, the minimum tally for the main Hawaiian Islands other than Ni'ihau and Lehua, and pup counts at all

locations. CAPTURE estimates have associated standard deviations and assumed normal error distributions (Otis et al. 1978). For sites where the minimum count was adjusted based on discovery curves, we characterized uncertainty in the unidentified proportion of the population using the fitted beta distributions described above. The estimates for Necker and Nihoa have an empirical distribution reflecting the observed relationship between standardized counts and the total population size (A. L. Harting et al. unpubl.). For Ni'ihau and Lehua, we used the mean correction factor (proportion of time spent on land) and estimated variance from 23 telemetry deployments on seals (Wilson et al. in press). Examination of a quantile-quantile plot of these observations confirmed that their distribution is approximately normal.

We used a Monte Carlo approximation to generate a distribution of range-wide abundance. We experimented with increasing numbers of random trials and determined that the resulting distributions (mean, median, and quantiles) stabilized with 30 000 trials. Thus, 30 000 random draws with replacement from each of the variable site-specific abundance distributions were summed, added to the fixed tally from the sites with invariant estimates (including pups), and stored to obtain a distribution of range-wide abundance.

For CAPTURE estimates, we drew random normal values from the distributions with means and standard deviations equal to those estimated. However, the symmetrical normal distributions often include values that fall below known minimum abundance (Baker 2004). Therefore, when a random draw was lower than the known minimum, that sample was discarded and replaced until 30 000 values greater than or equal to the known minimum were sampled. For the remaining Northwestern Hawaiian Islands sites with discovery curve information, random values were drawn from the fitted beta distributions representing the proportion of non-pups identified at the end of the field season (Fig. 2, and see Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n031p317_supp.pdf). The minimum tally for the site in question was then divided by each of these random proportions to obtain 30 000 estimates of non-pup abundance. For Necker and Nihoa, we simply randomly drew from the distributions of non-pup abundance (A. L. Harting et al. unpubl.). For Ni'ihau and Lehua Islands, we drew random normal values from a distribution with the mean equal to the mean beach count divided by the mean proportion of time ashore. Because the estimate was generated by dividing the mean count by a random variable (proportion of time spent on shore), we used the delta method to estimate the variance of the inverse of the proportion on shore (Seber 1982). Thus, let $\hat{N}$ = estimate of non-pup abundance; $\bar{h}$ = mean proportion of time (h) seals spend on land; C = mean non-pup count; $var(h)$ = variance of h

$$\hat{N} = C \frac{1}{\bar{h}} \tag{1}$$

According to the delta method:

$$var(\hat{N}) = \left[\left(C \frac{1}{\bar{h}} \right)' \right]^2 var(h) \tag{2}$$

$$var(\hat{N}) = \left(-\frac{C}{\bar{h}^2} \right)^2 var(h) \tag{3}$$

Based on Wilson et al. (in press), $\bar{h} = 0.370$, $var(h) = 0.00794$, so that

$$var(\hat{N}) = C^2 \times 0.423 \tag{4}$$

and the standard deviation (SD) is

$$SD(\hat{N}) = C \times 0.650 \tag{5}$$

Thus, the estimated abundance distribution of non-pups at Ni'ihau and Lehua Islands is normal, with mean $\hat{N}$ and SD = $C \times 0.650$.

RESULTS AND DISCUSSION

Sufficient data were available to generate range-wide abundance estimates for the Hawaiian monk seal in 2013 to 2015. Due to logistical constraints, counts were conducted on Necker Island only in 2013. Because this island represents only a small fraction of the total, and counts at Necker Island have been relatively stable (Table 1, A. L. Harting et al. unpubl.), we used the 2013 Necker Island estimate for 2014 and 2015.

At 4 subpopulations (Laysan and Lisianski Islands, Midway and Kure Atolls), there were from 6 to 18 reference years in which total enumeration was achieved, providing a basis for adjusting minimum counts in other years. However, there was only 1 year with total enumeration at Pearl and Hermes Reef, and this was never achieved at French Frigate Shoals. For the former site, we included 4 additional reference years when the total enumeration criterion was nearly, but not quite, achieved. In 3 of these years, only 1 new seal was identified in the final 98 to 108 h of field effort, and in 1 year, no new seals were detected in the final 73 h. At French Frigate Shoals, there were only 2 such years with near total enumeration. Thus, for this

Table 1. Site-specific and range-wide estimates of Hawaiian monk seal *Neomonachus schauinslandi* abundance in 2013 to 2015. Methods used to generate abundance estimates are DC: discovery curve analysis, Enum: total enumeration; CR: capture-recapture; CC: counts corrected for the proportion of seals at sea; Min: minimum tally. Median values are presented with (in parentheses) 95% confidence intervals of 30 000 random draws from abundance distributions where estimates of error are available. Note that the median range-wide abundance is not equal to the total of the individual sites' medians, because the median of sums may differ from the sum of medians for non-symmetrical distributions

Location	2013		2014		2015	
	Method	Estimate	Method	Estimate	Method	Estimate
Kure Atoll	DC	68 (68,82)	Enum.	75	Enum.	90
Midway Atoll	DC	53 (50,61)	DC	68 (61,84)	DC	64 (61,73)
Pearl & Hermes Reef	DC	140 (138,147)	DC	157 (146,175)	DC	145 (145,149)
Lisianski Isl.	DC	165 (147,216)	DC	143 (140,159)	DC	151 (151,157)
Laysan Isl.	DC	205 (205,215)	CR	226 (217,243)	DC	244 (243,256)
French Frigate Shoals	DC	181 (179,195)	DC	175 (174,191)	CR	193 (189,198)
Necker Isl.	CC	64 (46,113)	No surveys in 2014–2015		Used estimate from 2013	
Nihoa Isl.	CC	102 (74,182)	CC	111 (80,196)	CC	117 (83,204)
Ni'ihau/ Lehua	CC	151 (88,213)	CC	128 (77,179)	CC	102 (64,140)
Other main Hawaiian Isl.	Min.	144	Min.	147	Min.	145
Range-wide		1291 (1206,1410)		1309 (1233,1420)		1324 (1263,1430)

site, we used those 2 years combined with the 5 Pearl and Hermes Reef reference years, reasoning that these are both similarly-sized large atolls so that discovery curve patterns would be comparable.

Range-wide abundance estimates (median of distributions) and 95% confidence intervals are presented in Fig. 3. Site-specific abundance distributions (Table 1, Figs. S2–S4 in the Supplement) generated using the Monte Carlo approximation process demonstrate the relative size of the various portions of the total population in 2013 to 2015. The minimum tally of non-pups in the main Hawaiian Islands excluding Ni'ihau and Lehua Islands varied little: 123 in 2013, 132 in 2014, and 130 in 2015. The total number of

pups counted range-wide was 158, 170, and 198 in 2013, 2014, and 2015, respectively.

This new abundance estimation method is a great improvement over the status quo, which characterized abundance trends based only on a portion of the species' range. It also incorporates new information for adjusting counts at Necker, Nihoa, Ni'ihau, and Lehua Islands based on region-specific observations of the proportion of time seals spend on shore. Estimated uncertainty of the 2013 to 2015 estimates is relatively small, with coefficients of variation ranging from 0.033 to 0.040. Still, we acknowledge that these range-wide abundance estimates are somewhat negatively biased, primarily due to incomplete identification of seals in the main Hawaiian Islands. Sightings information about monk seals using Lanai and Kahoolawe Islands is sporadically reported. Counts of seals at remote Ka'ula Rock are rarely obtained. Fortunately, these sites appear to host relatively few seals compared to the remaining, much more thoroughly surveyed, main Hawaiian Islands. In the Northwestern Hawaiian Islands, when field camps are of insufficient duration to achieve total enumeration, closed capture-recapture estimates are used when available, and Baker (2004) showed that these tend to be slightly negatively biased. Estimates based on adjusted minimum counts at Pearl and Hermes Reef and French Frigate Shoals are likely somewhat negatively biased because most of the discovery curve reference data for those sites were from years when the total enumeration criterion was not quite met. Finally, the proportion of the true pup production detected is subject to negative bias depending upon
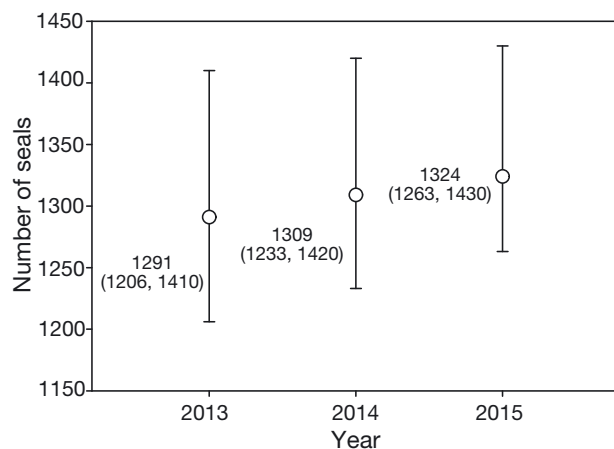

Fig. 3. Range-wide abundance estimates for Hawaiian monk seals *Neomonachus schauinslandi* from 2013 to 2015. Medians are shown (open circles) with 95% confidence limits (bars; exact values in parentheses)

the duration and timing of field effort, which vary without a consistent temporal trend.

A prolonged decline in abundance of Hawaiian monk seals in the Northwestern Hawaiian Islands has been well documented since systematic studies of the species commenced in the late 1950s (Kenyon & Rice 1959). While the individual subpopulations from Kure Atoll to French Frigate Shoals have exhibited asynchronous dynamics at times (some declining, others stable or increasing), their total abundance has dwindled for several decades (Ragen & Lavigne 1999, Carretta et al. 2015). However, the more recent expansion of the seal population in the main Hawaiian Islands and population growth and stability at Nihoa and Necker Islands, respectively, suggest that the trend for the whole species is less bleak (Baker et al. 2011, A. L. Harting et al. unpubl.). The 3 range-wide abundance estimates presented here (Fig. 3) are encouraging — the point estimate for 2014 is higher than for 2013, and 2015 is even higher. These estimates are subject to uncertainty and negative bias as discussed above, and the confidence intervals for all years largely overlap one another. Thus, it is not currently possible to unequivocally conclude whether the current trend is declining, stable, or increasing, but even the lack of evidence for continued decline is a welcome change for this endangered species. Also encouraging is that the estimates for individual sites, even those subpopulations that had been declining over the long term, appear relatively stable if not increasing over the past 3 yr (Fig. S5 in the Supplement). The point estimates for Ni'ihau and Lehua Islands decreased from 2013 to 2015, but these estimates are based on the expansion of just 1 or 2 counts per year and exhibit the greatest relative uncertainty (Figs. S2–S4 in the Supplement). Ideally, continued commitment to conducting surveys that inform these estimates will allow for more conclusive interpretation of both site-specific and range-wide abundance trends for this species.

LITERATURE CITED

Baker JD (2004) Evaluation of closed capture-recapture methods to estimate abundance of Hawaiian monk seals, *Monachus schauinslandi.* Ecol Appl 14:987–998

Baker JD, Johanos TC (2004) Abundance of the Hawaiian monk seal in the main Hawaiian Islands. Biol Conserv 116:103–110

Baker JD, Harting AL, Johanos TC (2006) Use of discovery curves to assess abundance of Hawaiian monk seals. Mar Mamm Sci 22:847–861

Baker JD, Harting AL, Wurth TA, Johanos TC (2011) Dramatic shifts in Hawaiian monk seal distribution predicted from divergent regional trends. Mar Mamm Sci 27:78–93

Cahoon MK (2011) The foraging ecology of monk seals in the main Hawaiian Islands. MSc thesis, University of Hawaii at Manoa, Honolulu, HI

Cahoon MK, Littnan CL, Longenecker K, Carpenter JR (2013) Dietary comparison of two Hawaiian monk seal populations: the role of diet as a driver of divergent population trends. Endang Species Res 20:137–146

Carretta JV, Oleson EM, Weller DW, Lang AR and others (2015) US Pacific marine mammal stock assessments: 2014. Tech Memo NOAA-TM-NMFS-SWFSC-549. US Department of Commerce, NOAA, La Jolla, CA

Delignette-Muller ML, Dutang C (2015) fitdistrplus: an R package for fitting distributions. J Stat Softw 64:1–34

Evenhuis NL, Eldredge LG (eds) (2004) Natural history of Nihoa and Necker Islands. Bishop Museum Press, Honolulu, HI

Gilmartin WG, Johanos TC, Eberhardt LL (1993) Survival rates for the Hawaiian monk seal (*Monachus schauinslandi*). Mar Mamm Sci 9:407–420

Gobush KS, Farry SC (2012) Non-lethal efforts to deter shark predation of Hawaiian monk seal pups. Aquat Conserv 22:751–761

Harting AL, Baker JD, Becker BL (2004) Nonmetrical digital photo identification system for the Hawaiian monk seal. Mar Mamm Sci 20:886–895

Harting AL, Johanos TC, Littnan CL (2014) Benefits derived from opportunistic survival-enhancing interventions for the Hawaiian monk seal: the silver BB paradigm. Endang Species Res 25:89–96

Henderson JR, Johanos TC (1988) Effects of tagging on weaned Hawaiian monk seal pups. Wildl Soc Bull 16:312–317

Hiruki LM, Stirling I, Gilmartin WG, Johanos TC, Becker BL (1993) Significance of wounding to female reproductive success in Hawaiian monk seals (*Monachus schauinslandi*) at Laysan Island. Can J Zool 71:469–474

Johanos TC (2015a) Hawaiian Monk Seal Research Program Hawaiian monk seal survey data collected in the Hawaiian Archipelago, 1962-2015. US National Oceanographic Data Center. https://inport.nmfs.noaa.gov/inport/item/5676

Johanos TC (2015b) Hawaiian Monk Seal Research Program Hawaiian monk seal master identification records (annual) collected in the Hawaiian Archipelago, 1962–2015. US National Oceanographic Data Center. https://inport.nmfs.noaa.gov/inport/item/12939

Johanos TC, Becker BL, Ragen TJ (1994) Annual reproductive cycle of the female Hawaiian monk seal, *Monachus schauinslandi.* Mar Mamm Sci 10:13–30

Johanos TC, Harting AL, Wurth TA, Baker JD (2014) Range-wide movement patterns of Hawaiian monk seals. Mar Mamm Sci 30:1165–1174

Kenyon KW, Rice DW (1959) Life history of the Hawaiian monk seal. Pac Sci 13:215–252

Littnan C, Harting A, Baker J (2015) *Neomonachus schauinslandi*. The IUCN Red List of Threatened Species 2015:

e.T13654A45227978. http://dx.doi.org/10.2305/IUCN.UK.2015-2.RLTS.T13654A45227978.en

➤ Lopez J, Hyrenbach KD, Littnan C, Ylitalo GM (2014) Geographic variation of persistent organic pollutants in Hawaiian monk seals *Monachus schauinslandi* in the main Hawaiian Islands. Endang Species Res 24:249–262

Otis DL, Burnham KP, White GC, Anderson DR (1978) Statistical inference from capture data on closed animal populations. Wildl Monogr 62:1–135

➤ Parrish FA, Marshall GJ, Buhleier B, Antonelis GA (2008) Foraging interaction between monk seals and large predatory fish in the Northwestern Hawaiian Islands. Endang Species Res 4:299–308

Ragen TJ, Lavigne DM (1999) The Hawaiian monk seal: biology of an endangered species. In: Twiss JR, Reeves RR (eds) Conservation and management of marine mammals. Smithsonian Institution Press, Washington, DC, p 224–244

Rexstad EA, Burnham KP (1991) User's manual for interactive Program CAPTURE. Colorado Cooperative Fish and Wildlife Research Unit, Colorado State University, Fort Collins, CO

Seber GAF (1982) The estimation of animal abundance and related parameters. MacMillan, New York, NY

White GC, Anderson DR, Burnham KP, Otis L (1982) Capture-recapture and removal methods for sampling closed populations. Los Alamos National Laboratory, Los Alamos, NM

➤ Wilmshurst JM, Hunt TL, Lipo CP, Anderson AJ (2011) High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. Proc Natl Acad Sci USA 108:1815–1820

Wilson K, Littnan CL, Read AJ (in press) Movements and home ranges of monk seals in the main Hawaiian Islands. Mar Mamm Sci